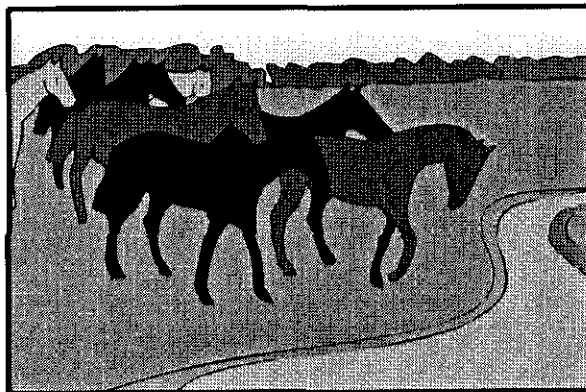# APPENDIX E

SUBSIDENCE REPORTS

EVALUATION OF SUBSIDENCE
IN THE SACRAMENTO-SAN JOAQUIN DELTA

By
The Subsidence Sub-Team
of the Levees and Channels Technical Team

DRAFT

October 22, 1998

Summary

Island subsidence has played a key role in bringing the Delta islands to where they are today; relatively tall levees (8 to 25 feet above sea level) protecting interiors (up to 22 feet) below sea-level. Island subsidence is, and will continue to be, an important issue in the Delta, especially regarding land use. The Subsidence Subteam, however, was tasked with addressing the relation of island subsidence to levee system integrity. Since the levees ring the islands and lose ground elevation on their own due to the addition of levee material, processes at the perimeter of the island are very different than what occurs in the center of the islands.

The risk to levee integrity from island subsidence has diminished because of improved levee maintenance practices and land management practices. Island subsidence rates have decreased, and levee construction techniques have improved. In addition, a zone of influence extending from the levee crest to some distance inland has been identified, beyond which interior island subsidence will not affect levee integrity. This report addresses subsidence as it affects levee integrity within the zone of influence adjacent to levees.

Goal

The goal of the Subsidence element of the Levee Program is to reduce or eliminate the risk to levee integrity from subsidence.

Scope

The Long Term Levee Protection Plan focuses on subsidence that affects the levee system. This report describes Delta conditions, causes of subsidence, subsidence as it affects levee integrity, mitigation options related to levee integrity, and target areas for subsidence control based on the best available information. Subsidence issues, concerns, and solutions will also be addressed in the Ecosystem Restoration Program, which will pursue subsidence control actions that promote habitat restoration where opportunities exist both on the levees and in the island interiors.

Conditions In The Delta

Surface and subsurface materials. (References 5 through 12)

The present-day Delta deposits began to form during the end of the last glacial period, 7,000 to 11,000 years ago as sea level began to rise (Ref 4). As the Delta evolved, tributaries formed a series of channels, natural levees, berms, islands and sloughs. The major rivers and channels periodically incised,

then were backfilled as the climate changed. Tules, reeds, and other fibrous aquatic plants growing at water level were preserved as peat beds when post glacial sea levels rose slowly and inundated the Delta. Under natural conditions, the islands received fine- and coarse-grained sediments during river floods. As a result, the subsurface sedimentary profile generally contains inter-bedded layers of sand, silt, clay and peat of varying thickness. The complexity of subsurface conditions is reflected in the wide variety of surface soil types found throughout the delta. The surficial materials encountered in the Delta include mineral soils, mineral organic complexes, organic soils, and peat.

Ground surface elevations. (Reference 11, Delta Atlas)

Ground surface elevation varies throughout the Delta from the high ground along the levee crests to the low ground in the island interiors. Levee crest elevations generally range from about 8 to 25 feet above sea level. A significant portion of Delta land surface is below sea level. Lowest surface elevations are on the order of 22 feet below sea level. Refer to Figure 1 (based upon a 1974 survey) for an indication of the extent of land surface elevation below sea level. Updated ground surface elevation data is needed.

Island Subsidence and Levee Subsidence

Definition

Subsidence is a downward movement of the ground surface over time. For the purposes of this report, "Island subsidence" refers to the loss of interior Delta island ground surface elevation. The downward movement of the levee itself, generally due to an application of a load, is referred to as "levee subsidence." The causes and impacts of levee subsidence are much different than the causes and impacts of island subsidence, but the primary causes of both will be discussed here together because there is an overlap of contributing causes.

Causes of Island Subsidence and Levee Subsidence (References 1 through 12)

Island subsidence and levee subsidence in the Delta are mainly caused by near-surface processes including consolidation/settlement, shrinkage, and aerobic decomposition. Other near-surface causes of island and levee subsidence include anaerobic decomposition, wind erosion, and burning. Deep seated causes of subsidence include the withdrawal of oil, natural gas, and water, and tectonic activity. These causes were assumed to contribute little to present-day subsidence. However, some consider natural gas withdrawal to be an important contributor (Ref. 1).

a) Consolidation/settlement: Consolidation/settlement occurs in response to an increase in load, such as when ground water is removed or when materials are deposited in an area by

humans or nature. Consolidation due to levee building (increasing loads on foundation materials) is the primary cause of levee subsidence. Consolidation also occurs due to increased effective stress on underlying peat and decreased buoyant forces supporting peat as a result of incremental dewatering (Ref. 1).

b) Shrinkage: Shallow de-watering is considered a cause of island and levee subsidence because it leads directly to shrinkage and drying of soils above the water table, consolidation of soils just above the water table, and leads to aerobic decomposition of organic soils above the water table. The relative effect of each of these factors depends on the amount of organic matter in the soil, the depth of de-watering, and climate. With each incremental lowering of the water table, the contribution to island subsidence from shrinkage, consolidation, and oxidation are all high. With time, long-term island subsidence is sustained by oxidation. Shrinkage is governed by the initial moisture content and the organic matter content. Fine grained organic soils and peat can shrink 50% or more in volume.

c) Aerobic decomposition (microbial oxidation): Long-term island subsidence is sustained primarily by the microbial oxidation of soil organic carbon. The peat soils contain a complex mass of carbon. Microorganisms such as bacteria and fungi use it as an energy source resulting in peat decomposition and the release of carbon dioxide (CO_2) under drained, oxygen-rich conditions. Studies by the Department of Water Resources and the US Geological Survey (Deverel and Rojstaczer, 1996) demonstrate that the amount of oxidation is proportional to the soil temperature and moisture content.

Oxidation rates increase with temperature, higher pH, and higher organic matter content of the soil. There is an optimum moisture content for oxidation; oxidation decreases at very high and very low moisture contents. Drainage and tillage promote aerobic decomposition, but island subsidence is not substantially affected by crop type. Island subsidence due to oxidation will decrease with time as the organic matter content in the upper soil decreases and the relative percentage of mineral constituents increases. There does not appear to be a correlation between peat thickness and subsidence rates. There is a direct correlation between depth to the water table and the amount of subsidence due to microbial oxidation. The higher the water table, the less the island subsidence.

Levee Subsidence (Reference 4,12,13)

Most levee subsidence is caused by the weight of the levee fills compressing the foundation materials. The foundation materials underlying the levees vary throughout the Delta from various thicknesses of peat soils to mineral soils. Rate of levee building and foundation conditions govern levee subsidence rates and the total amount of subsidence. Geotechnical engineering fundamentals must be applied to *safely and economically build new levees and rehabilitate existing levees founded on weak,*

compressible materials.

Regardless of load application to the levees, the levees settle with time. In the 1960's, a set of curves was developed for estimating crest settlement with respect to variables of peat thickness, height of levee, and age of levee. These curves were updated to incorporate recent data, and are included as Figures 8 and 9. These curves of predicted movement were compared with actual crest elevation measurements on selected islands, and results indicated that measured settlements were generally comparable to calculated values and ranged from 2 to 7 inches per year (Ref 5).

There is a great deal of information on the causes and effects of interior island subsidence, but interior island subsidence has never been directly linked in publications to levee subsidence. A recent Corps of Engineers geotechnical report stated that, "Independent of the island subsidence, the levees settle with time. This settlement is caused primarily as a result of consolidation and plastic flows of the underlying organic soils. Since island subsidence is independent of levee settlement, numerous levee geometries are produced (Ref. 5)." Although "independent," the Corps document recognizes that island subsidence may influence levee integrity. This document also presents the concept of a "zone of influence(ZOI)," beyond which interior island subsidence does not affect levee integrity.

The Corps developed curves for estimating settlement of fills placed on organic material (figures 6 and 7). Considerable judgement should be exercised in using these curves. As examples, settlements were calculated using these curves for a 4.5-foot-thick stabilizing berm and a 2-foot-thick subsidence control cap. Assuming a 45-foot-thick unconsolidated peat layer, the 4.5-foot thick fill causes approximately 13.8 feet of total settlement at an initial time-averaged rate of about 6 inches per year, and the 2.5-foot-thick soil cap causes approximately 6.0 feet of total settlement at an initial time-averaged rate of about 2 inches per year. Based on experience, the calculated settlements are too high and the initial settlement rates are too low. It is common in the Delta for new fill to settle rapidly and total settlement to be roughly equal to the applied fill layer thickness. When compared to interior island subsidence, levee subsidence (settlement) can be significantly greater than island subsidence and is probably the primary reason for performing a high level of levee maintenance.

Near-levee subsidence will effect levee stability. This subsidence is the result of de-watering and the associated consolidation, shrinkage and decomposition of high organic content materials near the levee. Engineering analysis indicates there is a discrete distance away from a levee, a zone of influence, beyond which subsidence no longer adversely affects levee integrity.

Zone of Influence

The zone of influence is an area from the crest of the levee to some distance inland where island subsidence may impact levee integrity. Beyond this zone of influence, island subsidence will not affect levee integrity. Although the ZOI for a reach of levee can only be determined using site-specific data, geotechnical engineering analysis and judgement can be applied to characterize its extent. The Subteam

estimated the ZOI for planning purposes. Based upon available information and engineering judgement, the ZOI is estimated to range from 0 to 500 feet from the levee crest, depending on site-specific conditions. Since the ZOI is a site-specific characteristic, it could change with time as site conditions change. The following engineering analyses could contribute to the determination of the ZOI on a site-specific basis.

a) Static stability: geotechnical engineers use stability analysis to determine factors of safety and critical failure modes for earthen structures (Refer to Figure 2). Numerous Delta levee stability analyses indicate that there is a definable distance from the levee beyond which soil properties and changes do not affect levee stability. The limiting distance often turns out to be approximately 3- to 4-times the thickness of the peat layer beneath the levee. For example, the thickness of the deepest peat layer in the Delta is approximately 60 feet (Refer to Figure 3). Therefore, any island subsidence beyond 180-to 240 feet from the levee would probably not affect static levee stability. If the peat layer was less thick, which it is for most of the Delta, then the distance would be smaller for static stability.

b) Seepage: Flow net analyses indicate that critical exit gradients are most likely to be exceeded at or in close proximity to the levees. Critical gradients are less likely to be exceeded as the distance from the levee increases. In addition, flow net analyses indicate that drainage ditches located near the levees can have a detrimental effect on levee seepage (Refer to Figure 4). Island subsidence adjacent to levees would normally occur landward of any drainage ditch, and could affect seepage by decreasing the seepage path. A shorter seepage path leads to increased seepage. Increased seepage may lead to piping and levee stability problems. Determining a general seepage zone of influence is difficult, as it is dependent upon complex local soil features.

c) Deformation: Deformation is the spreading movement of soft soils in a reaction to load. Deformation can also be the result of loss of support at the levee toe, i.e, subsidence, and excavation of a drainage ditch. The Sherman Island deformation analysis report (ref 13) provided analysis for an island that might be considered worst-case due to the thickness of the peat layer beneath the levee and the size (load) of the levee. Although the Sherman Island analysis did not consider the impact of future island subsidence on deformation, the information indicates that there is a distance beyond which deformations do not occur. For the computer deformation modeling, a boundary condition was set at approximately 300 feet from the crest of the levee, a distance beyond which deformation did not occur. Extreme future island subsidence may impact a levee, however, it is important to note that island subsidence occurs slowly, and that levees usually adjust to island subsidence as it occurs without detrimental effects on stability.

Clearly, the zone of influence will vary with site specific levee and foundation conditions and levee geometry. For example, the greater the height of the levee embankment above the island floor and the

greater the thickness of weak and compressible layers, such as peat, the wider is the zone of influence. Monitoring and research will later define this zone.

     <u>Hydrostatic Pressure.</u>

It has been commonly reported that subsidence of island interiors leads to increased hydrostatic pressure and levee instability. The implication that levees are now required to withstand a greater hydrostatic head of water than they were originally constructed is inaccurate in that the exterior water elevations remain the same. However, a decrease in the land mass resisting such hydraulic pressures may occur. Also, seepage forces and quantity will change due to increased hydraulic gradient. The decrease of island surface elevations is a contributing cause to the need for ongoing work to maintain the height and desired safety factor of the levees. Periodic levee improvements replace some of the land mass that was lost to subsidence.

Island Subsidence

Island Subsidence will be generally discussed here, because the focus of this report is subsidence as it impacts levee integrity. Island subsidence impacts levee integrity only when it occurs in proximity to a levee. Subsidence within the ZOI may decrease stability, increase seepage, increase the potential for piping, or increase the potential for levee deformation. At many locations, however, island subsidence is occurring too slowly or too far from the levee to be a threat to levee integrity. As long as the ZOI is protected from subsidence, levee integrity with respect to island subsidence should be assured. Although island subsidence outside of the ZOI does not impact levee integrity, it does impact the interior of Delta islands and their associated land uses.

Historically, time-averaged Delta-wide island subsidence rates have ranged from about 0.5 to 5.0 in/yr. Recent research indicates that island subsidence varied from about 0.2 in/yr to 1.2 in/yr for soils with organic contents varying between 20% and 50% (Reference 4, Rojstaczer and Deverel (1995). Subsidence rates are slowing . Present day subsidence rates were measured continuously from 1990 to 1992 by Deverel and Rojstaczer (1996) on Sherman and Jersey Islands and Orwood Tract. These authors reported rates of 0.2, 0.24, and 0.32 inch per year on Sherman, Jersey, and Orwood, respectively.

Island subsidence rates are site specific. No single island subsidence rate, such as the commonly used 2.5 to 3 inches per year, is valid for an entire island. Total island subsidence rates vary greatly and average island subsidence rates at specific sites appear to be diminishing with time. Rates may be greater in areas subjected to new or deeper de-watering.

Remedial Action and Prevention

The approach to control of levee subsidence will be fundamentally different than the means and methods employed to control island subsidence because of the differences in the primary causes of subsidence.

Levees (References 4 through 13)

Potential levee subsidence mitigation actions that should be considered are:

1)Thorough application of geotechnical engineering principles and practices in conjunction with proven construction methods. Levee subsidence will continue as long as levee building and repair continue to add loads onto weak compressible foundations.

2)Seepage control, de-watering efforts, excavations, and land management activities in proximity to levees must be modified to minimize adverse impacts to levee integrity.

3)Stability and drainage berms can be strategically located and sequentially constructed to minimize or prevent levee deformation.

4)Land leveling and other ground surface modifications (e.g. ditching) should be restricted within the zone of influence. High ground water levels and vegetative growth could be tolerated in some areas to accommodate measures aimed at reducing island subsidence due to oxidation.

Island Interiors, Including the ZOI (References 1 through 10)

Currently the best approaches to managing island subsidence, include a) minimizing or preventing the lowering of the groundwater level, b) capping or covering susceptible surface deposits with mineral soil, and c) permanent shallow flooding. and d)reverse wetland flooding.

Delineation of Target Areas for Subsidence

Subsidence control and monitoring will be most important for the western and central Delta islands, where the depth of organic soils are the greatest and the organic content of the deposits are commonly high. Previous attempts at prioritizing areas and islands, based on depth of peat and organic matter content, provide a good starting point for the development of a subsidence control and prevention program. It appears from this initial prioritization effort that only some islands and in some cases only parts of islands are affected. Refer to Figures 5-1 through 5-8, Subsidence Target Areas, for examples of islands and levee reaches most likely to be affected by subsidence (Deverel 1997, References 1&2). The number of levee miles potentially affected by subsidence was calculated using Figure 5. About

60% of the levees in the central and western Delta, but less than 30% of all the levees in the legal Delta, are targeted for subsidence control.

The objective of the maps in Figures 5-1 through 5-8 is to target areas for subsidence monitoring and control in the Delta. The general approach was to enter recent available data for the Delta for island subsidence rates, depth of peat soils and soil characteristics into a geographic information system (GIS). The estimates for rates of island subsidence and peat thickness are an improvement relative to the previous efforts by the Department of Water Resources because 1) the error in the estimated island subsidence rate is lower, quantifiable and the result of uniform elevation change measurements, and 2) the estimates for peat thickness are based on more recent and comprehensive data.. Also, the data was entered into a GIS which facilitated the evaluation of the data for delineation of target areas in greater areal detail than entire islands such as is presented in Department of Water Resources (1980).

The areal distribution of island subsidence rates and peat thickness is used to delineate target areas for additional data gathering and monitoring. The maps in Figures 5-1 through 5-8 used the estimated ZOI boundary of 500 feet around the islands. Within this boundary, the target areas are those where the island subsidence rates are high and there is substantial peat remaining. The target areas have time-averaged island subsidence rates greater than 1.5 inches per year (island subsidence rates ranged from about 0.4 inches per year to 5 inches per year) and peat thickness greater than 10 feet within the 500 foot boundary.

The term "peat" has been defined in many different ways. For the maps in Figure 5, "peat" will refer to peat or peaty mud of tidal wetlands comprised of the organic deposits derived from decayed vegetation that formed as the result of sea level rise during the last 7,000 to 11,000 years. The peat thickness shown on the maps was calculated as the difference between the basal elevation of peat or peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps(1976-1978). Atwater's delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soils surveys. The maps reflect borehole data collected as of 1980.

Monitoring

Subsidence monitoring should be tied to constructed base level projects because these areas provide the most economical opportunities for gathering more data in conjunction with construction explorations and monitoring. Subsidence monitoring should start with an evaluation of existing soils and their distribution and a determination of land surface elevation within Target Areas in the Delta. Efforts should be directed to areas on and adjacent to the levees, within the ZOI. From a new, continually updated database, a target list of levees and islands being impacted by subsidence can be maintained. Monitoring will allow subsidence control to be adaptively managed as levee rehabilitation goes forward. This monitoring efforts will be coordinated through CALFED's Comprehensive Monitoring,

Assessment, and Research Program (CMARP).

Conclusions

Although subsidence has caused problems in the past, and will continue to be a problem for island interiors, the potential impact of island subsidence on levee integrity has diminished. Land management and levee maintenance practices have improved and island subsidence rates have decreased. As long as island subsidence is adequately managed within the ZOI, levee integrity should be unaffected. Although the ZOI for a reach of levee can only be determined using site-specific data, the Subteam has estimated the ZOI for planning purposes. Based upon available information and engineering judgement, the ZOI is estimated to range from 0 to 500 feet from the levee crest depending on site-specific conditions. The ZOI could change with time as site-specific conditions change.

Subsidence control and monitoring will be most important for the western and central Delta islands, where the depth of organic soils are the greatest and the organic content of the deposits are commonly high. Previous attempts at prioritizing areas and islands, based on depth of peat and organic matter content, provide a good starting point for the development of a subsidence monitoring, control, and prevention program.
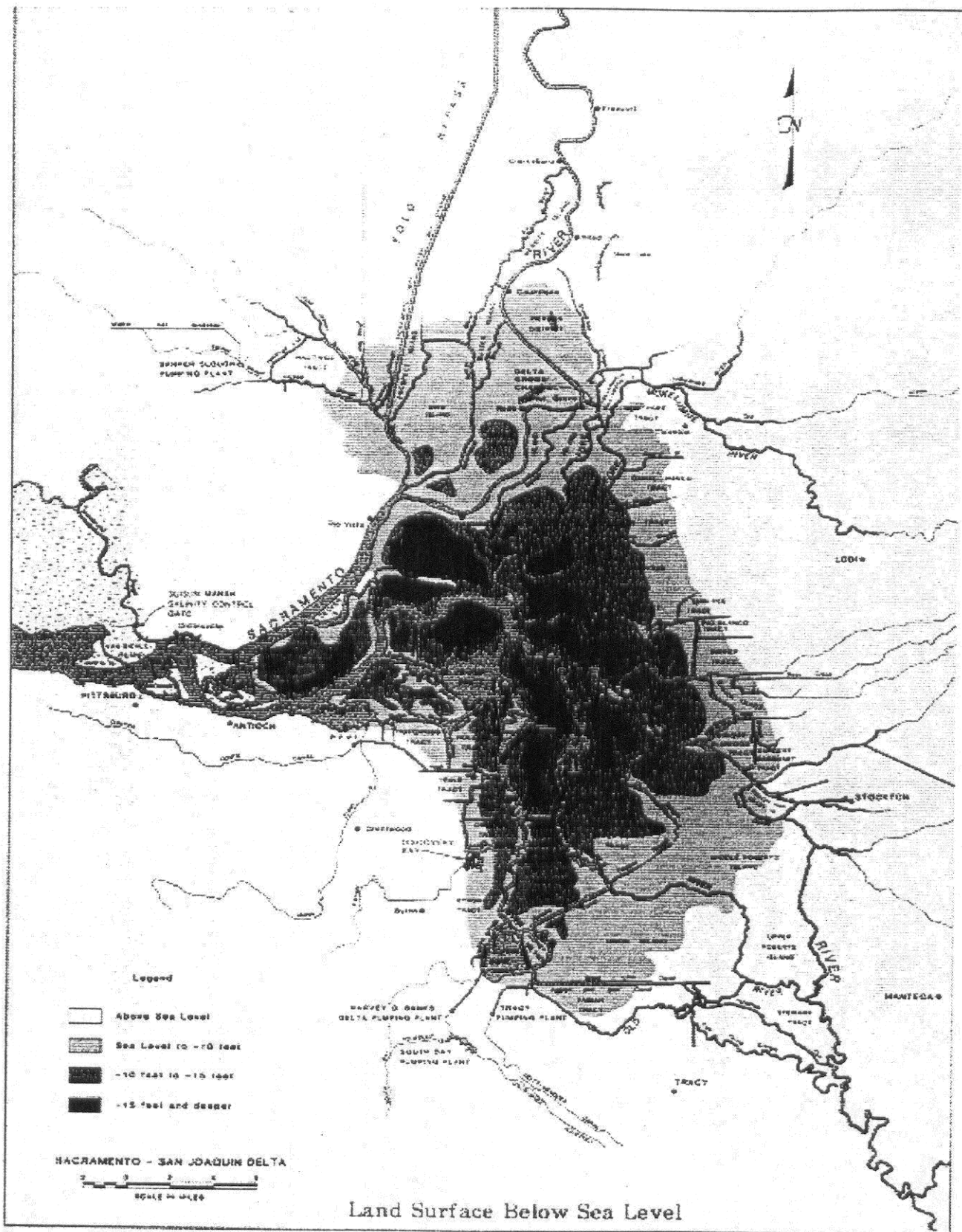
The levees identified as being target areas for subsidence remedial action and prevention will require screening and integration with other issues affecting levees such as seismic stability requirements, ecosystem restoration, and Delta water operations. This integration will allow a better prioritization of future subsidence remediation of the Delta levees.
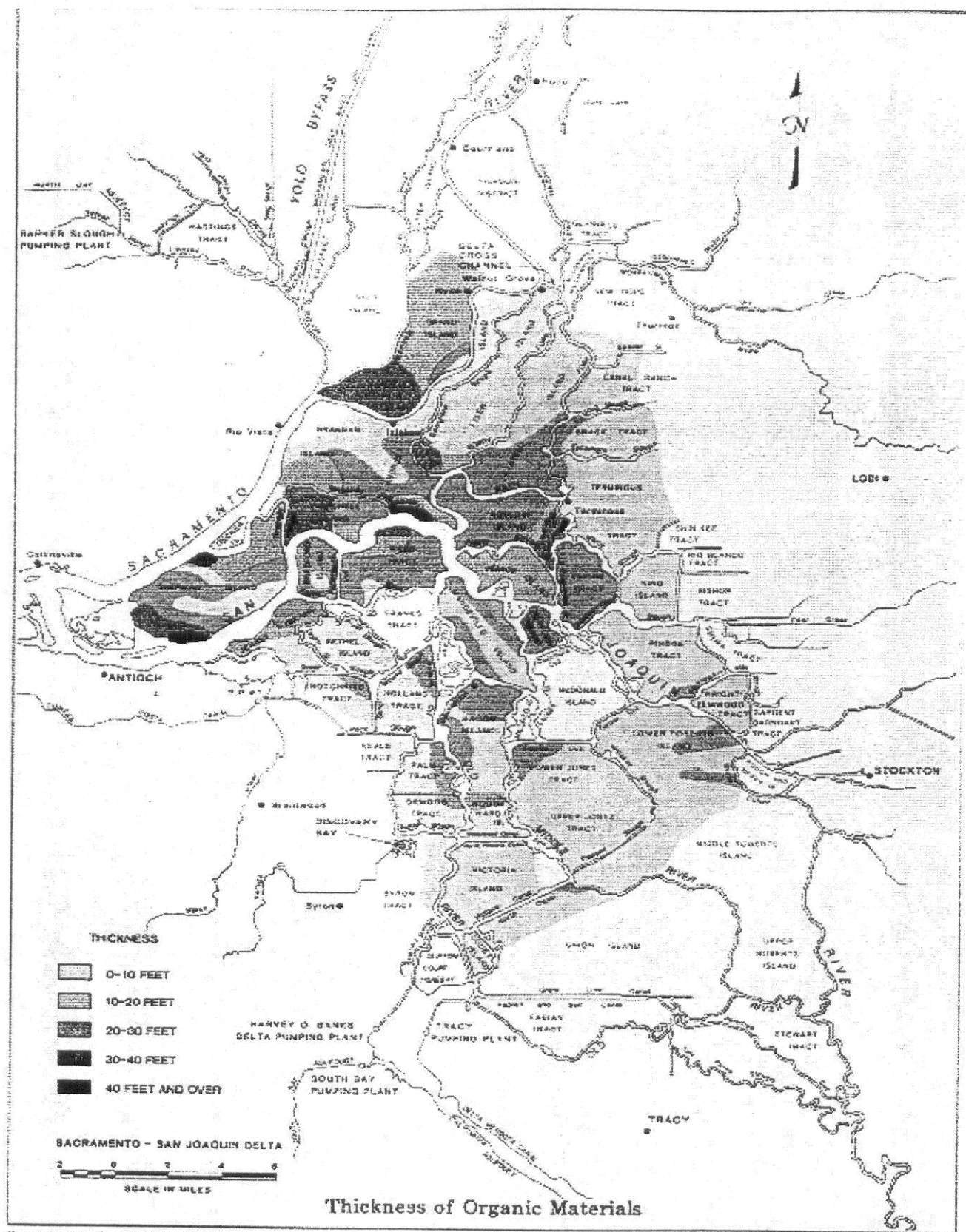
References: Subsidence in the Sacramento-San Joaquin Delta .

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2. Deverel, Steven J., (1997) ; Priority Areas For Subsidence Mitigation In The Sacramento-San Joaquin Delta. Draft.

3. Deverel, Steven J. and Stuart Rojstaczer, (1996); Subsidence of Agricultural Lands in the Sacramento-San Joaquin Delta, California: Role of Aqueous and Gaseous Carbon Fluxes; Water Resources Research, Vol.32, No.8, August 1996.

4. Rojstaczer, Stuart and Steven J. Deverel , (1995); Land Subsidence in Drained Histosols and Highly Organic Mineral Soils of California; Soil Science Society of America Journal Volume 59, No. 4 July-August 1995.

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9. Burke, Helen K. (1980); Report on Causes of Subsidence In The Sacramento-San Joaquin Delta and A Strategy For Controlling Its Rate.

10.California, State of (1980) ; Subsidence of Organic Soils In The Sacramento-San Joaquin Delta; The Resources Agency, Department of Water Resources

11. Weir, Walter W. (1949) ; Subsidence of Peat Lands of the Sacramento-San Joaquin Delta; Summary by Agricultural Extension Service, San Joaquin County.

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of Design.."

14. Foott, Sisson, and Bell (1992) ; Threatened Levees on Sherman Island. A reprint from Stability and Performance of Slopes and Embankments II Proceedings, GT Div/ASCE, Berkeley, CA, June 29-July 1, 1992.
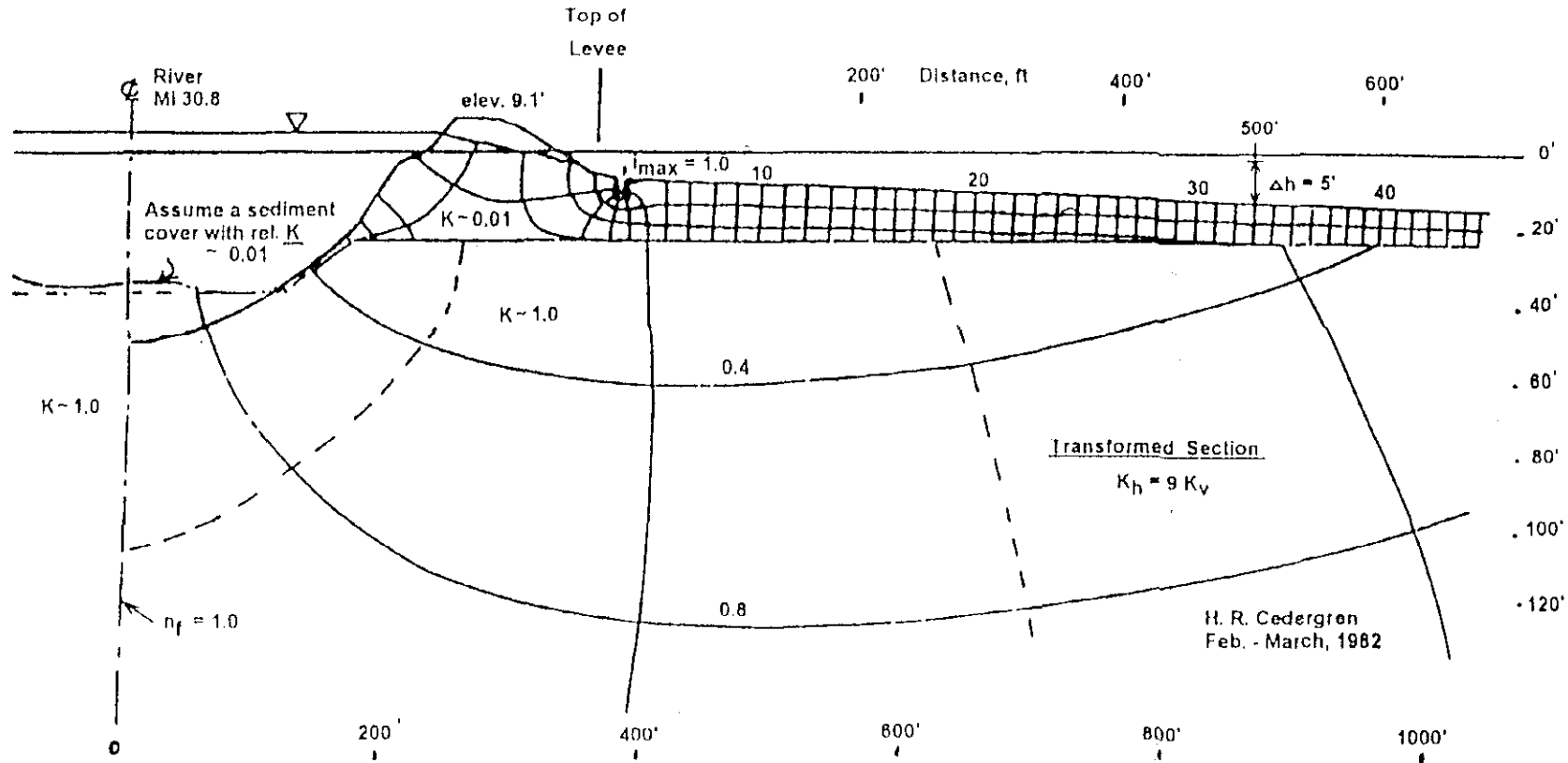
Land Surface Below Sea Level

Legend

☐	Above Sea Level
▦	Sea Level to -10 feet
▨	-10 feet to -15 feet
■	-15 feet and deeper

SACRAMENTO – SAN JOAQUIN DELTA

SCALE IN MILES

FIGURE 1

FIGURE 2 SLOPE STABILITY - OPTIMUM BERM SECTION (BERM FILL ONLY).

Thickness of Organic Materials

THICKNESS

0-10 FEET
10-20 FEET
20-30 FEET
30-40 FEET
40 FEET AND OVER

SACRAMENTO - SAN JOAQUIN DELTA

SCALE IN MILES

FIGURE 3

RINGE TRACT

Top of
Levee

River
Mi 30.8

200'   Distance, ft   400'   600'

elev. 9.1'

500'

0'

$i_{max} = 1.0$ 10   20   30 $\Delta h = 5'$ 40   - 20'

Assume a sediment
cover with rel. $\underline{K}$
~ 0.01

$K \sim 0.01$

$K \sim 1.0$. 40'

0.4   . 60'

$K \sim 1.0$ Transformed Section

$K_h = 9 K_v$. 80'

. 100'

$n_f = 1.0$ 0.8   H. R. Cedergren
Feb. - March, 1982   . 120'

200'   400'   600'   800'   1000'

0

STOCKTON DEEP WATER CHANNEL
SEEPAGE STUDY
FLOW NET NO. 6 - NA

Figure 5-1
Brannan & Andrus Islands
Target Areas

Subsidence Rate > 1.5 inches per year

Peat Thickness > 10 feet

500' Boundary

N

Department of Water Resources, Central District
Geographic Information Section
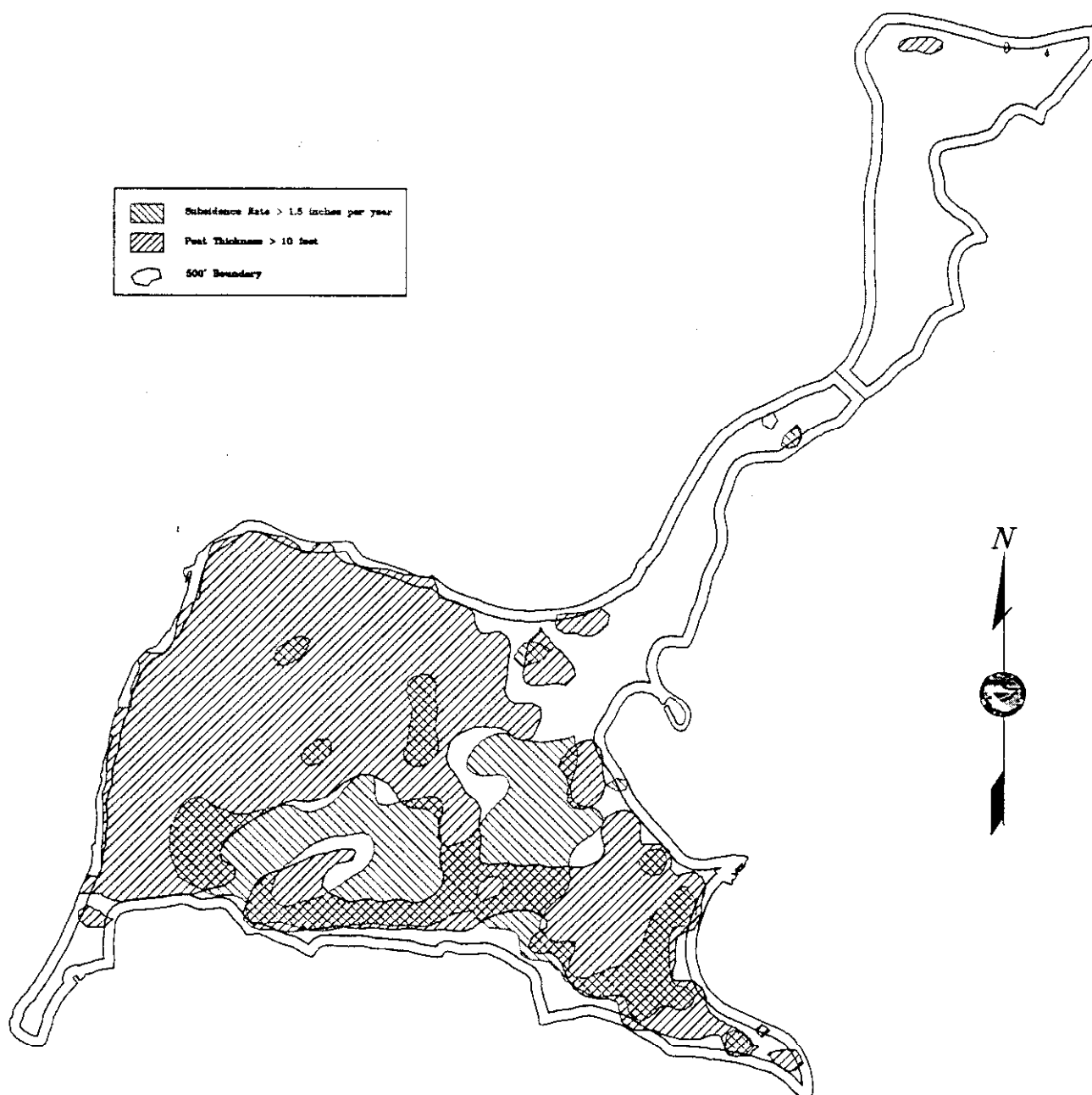
Figure 5-2

Staten & Tyler Islands
Target Areas

Subsidence Rate > 1.5 inches per year

Peat Thickness > 10 feet

500' Boundary

N

Department of Water Resources, Central District
Geographic Information Section
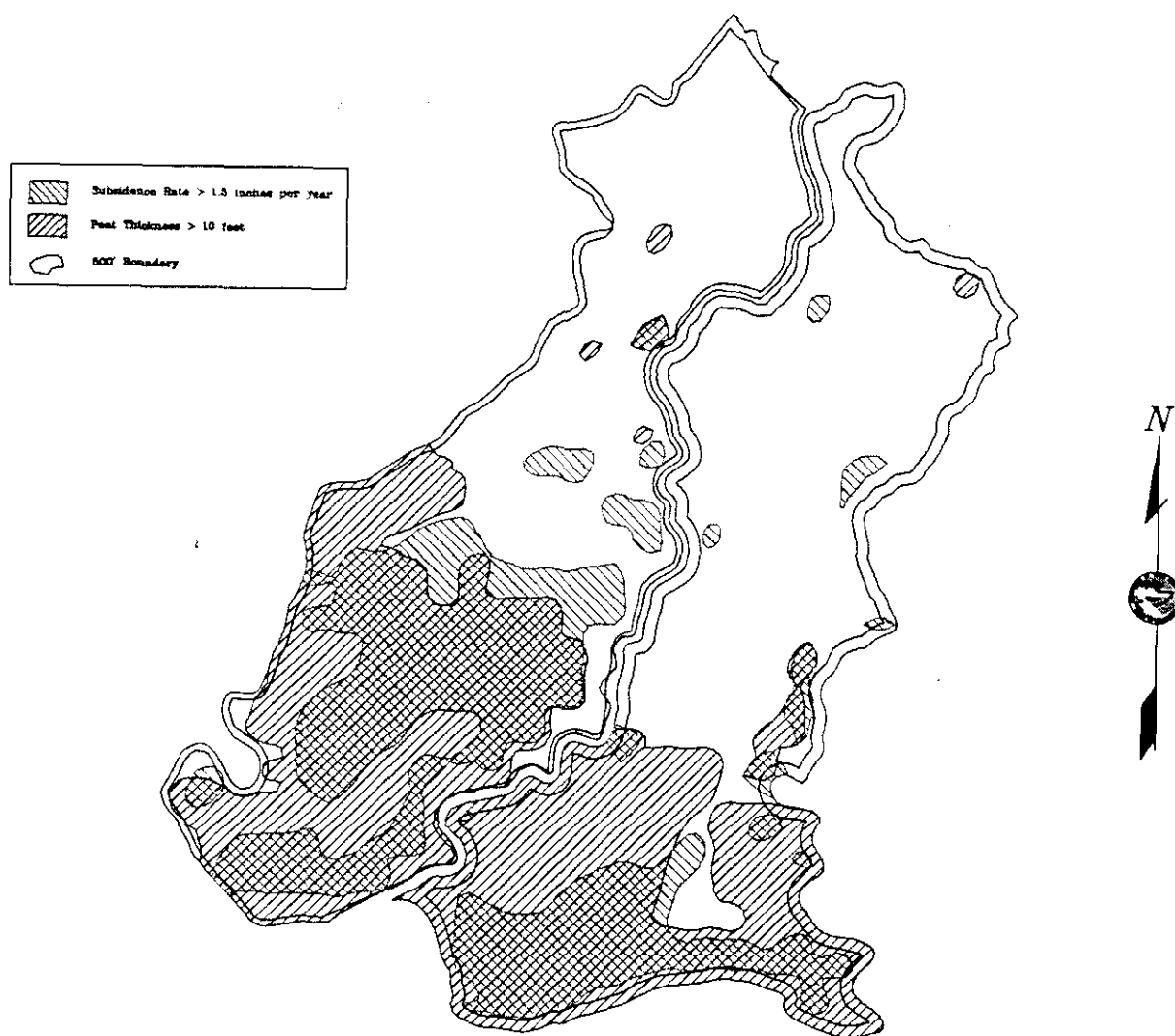
Figure 5-3

Bethel, Bradford, Jersey,
Twichell & Webb
Target Areas

N

Department of Water Resources, Central District
Geographic Information Section

	Subsidence Rate > 1.5 inches per year
	Peat Thickness > 10 feet
	800' Boundary
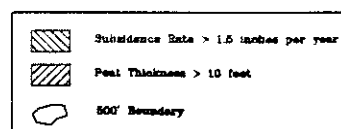
Figure 5-4

Sherman Island

Target Areas

N

Legend:
- Subsidence Rate > 1.5 inches per year
- Peat Thickness > 10 feet
- 500' Boundary

Department of Water Resources, Central District
Geographic Information Section
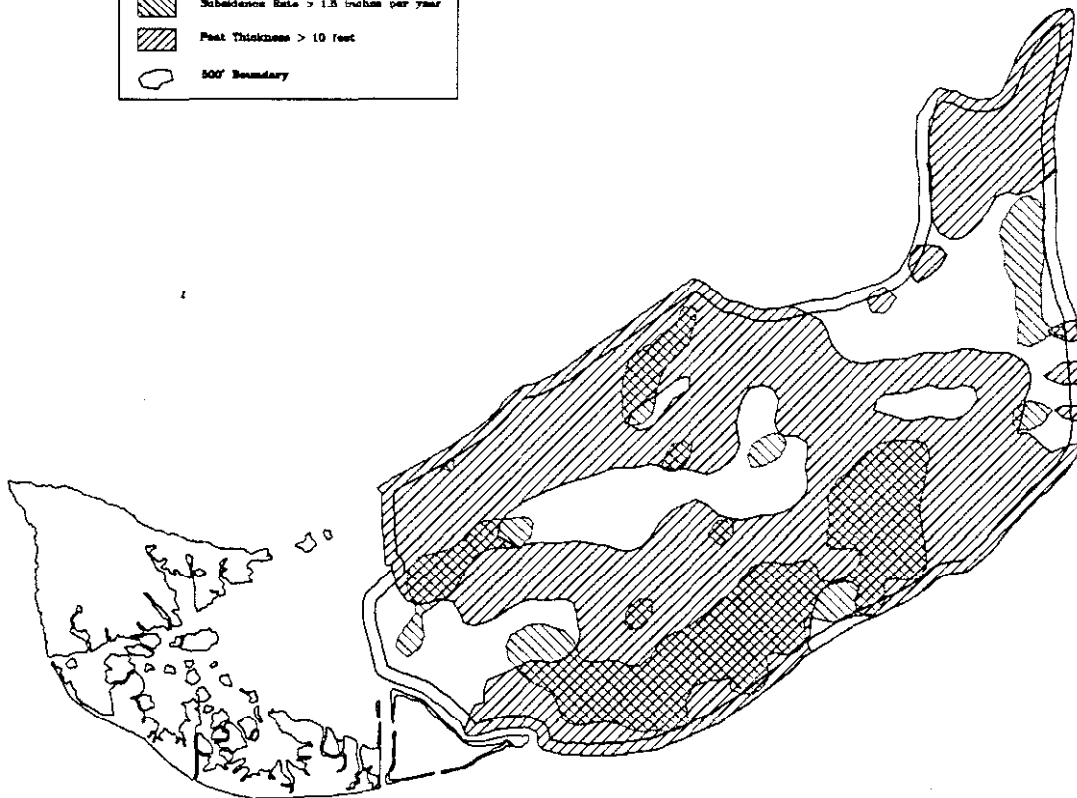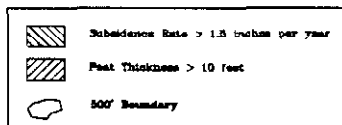
Figure 5-5

Bouldin, Empire, McDonald, Medford & Venice

Target Areas

N

▨	Subsidence Rate > 1.5 inches per year
▨	Peat Thickness > 10 feet
◯	500' Boundary

Department of Water Resources, Central District
Geographic Information Section
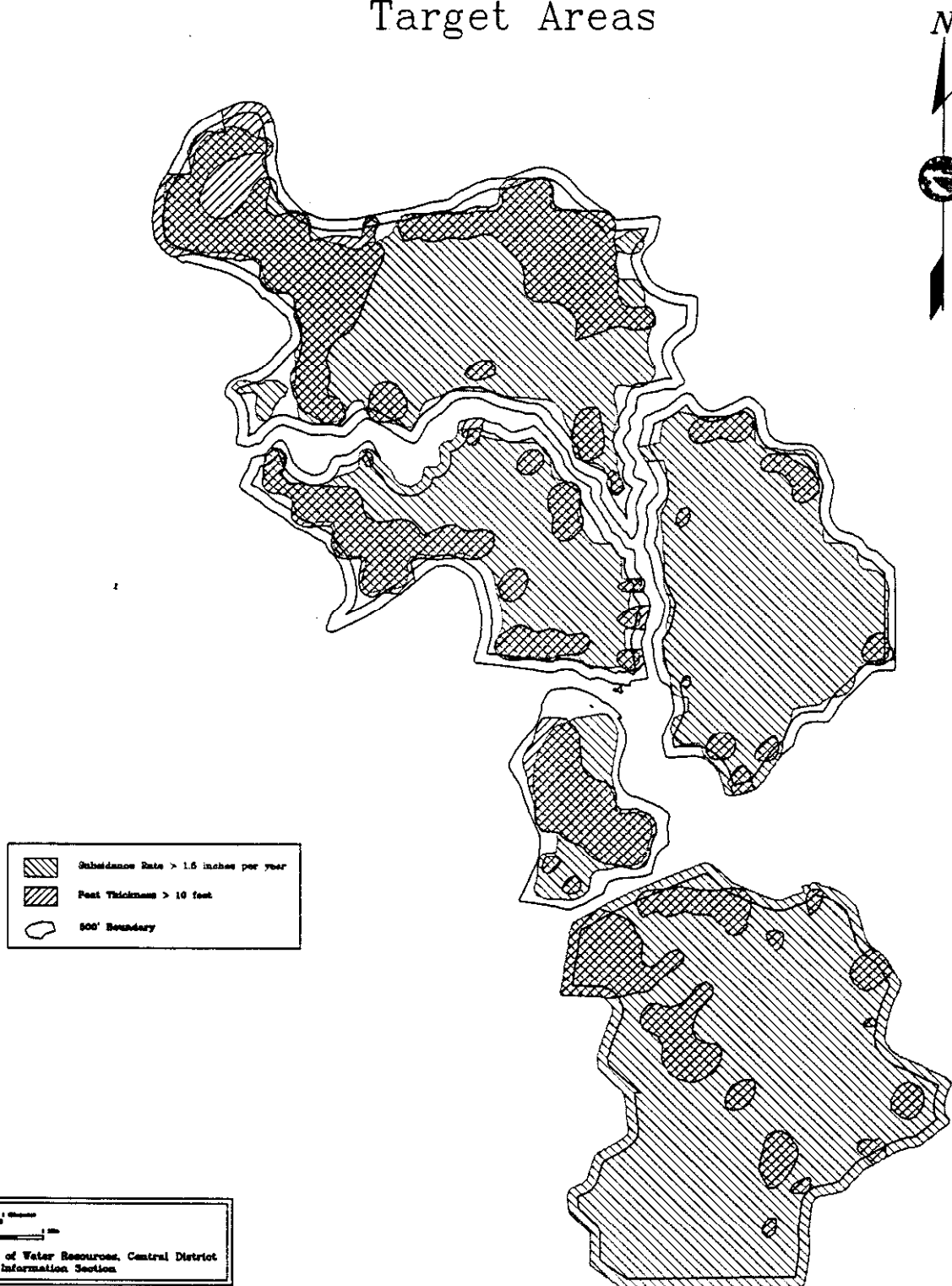
Figure 5-7
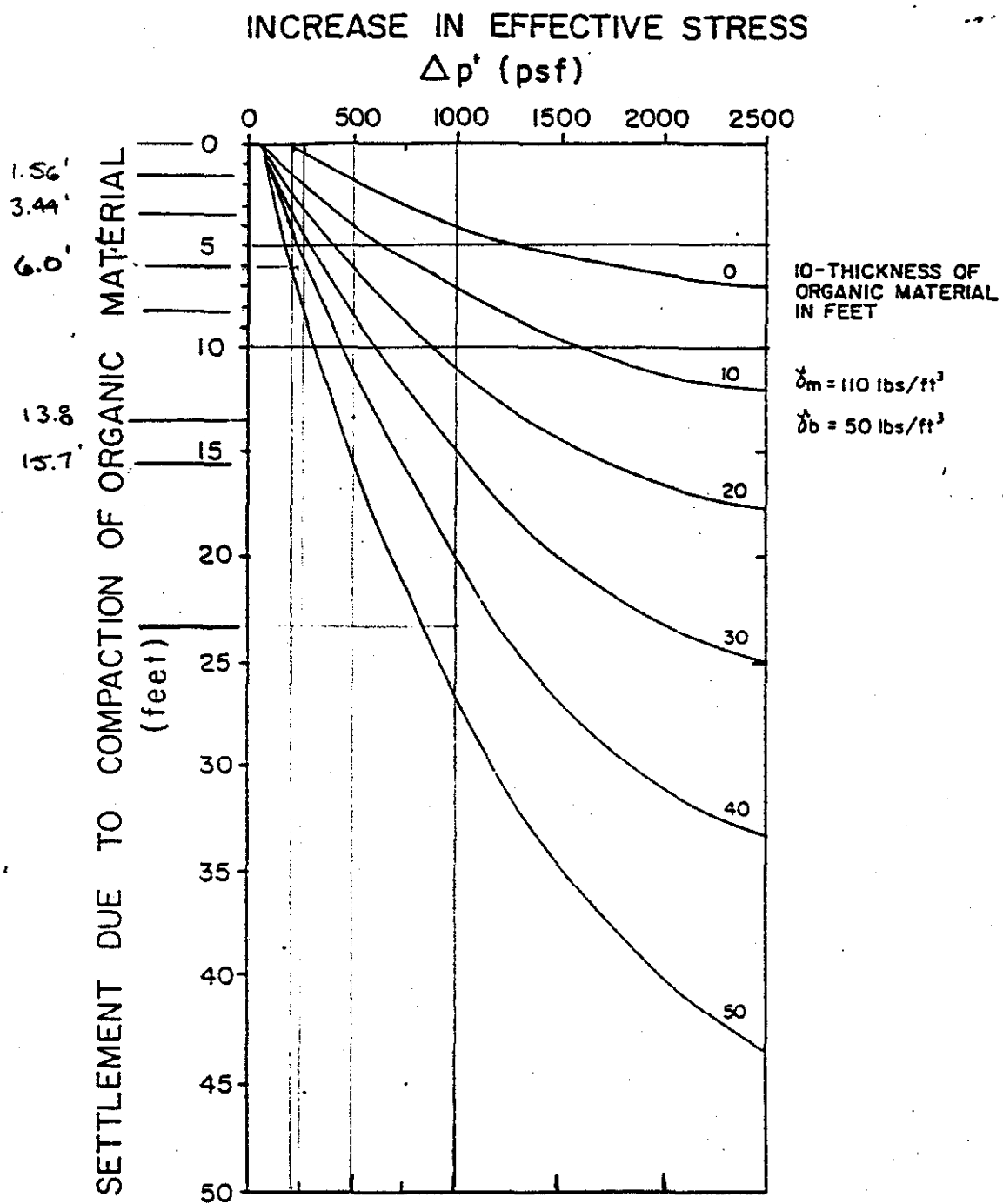## Bacon, Holland, Hotchkiss Palm, Quimby & Veale
Target Areas

N

Subsidence Rate > 1.8 inches per year

Peat Thickness > 10 feet

800' Boundary
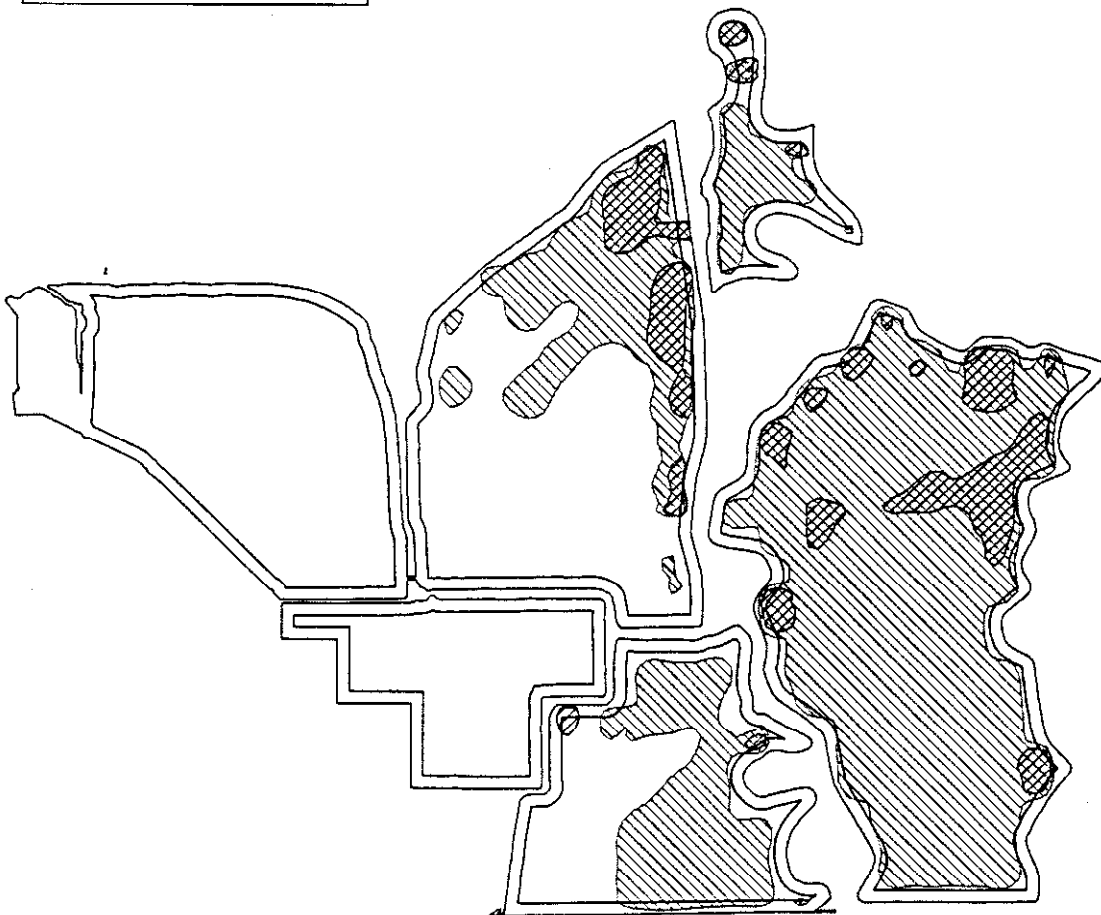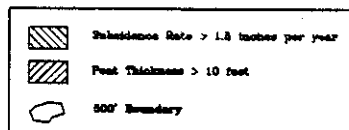
Figure 5-8

Upper & Lower Jones, Orwood
Woodward & Victoria

Target Areas

N

Subsidence Rate > 1.5 inches per year

Peat Thickness > 10 feet

600' Boundary

Department of Water Resources, Central District
Geographic Information Section

INCREASE IN EFFECTIVE STRESS
$\Delta p'$ (psf)

Chart axes and labels:

- Horizontal axis (top): 0, 500, 1000, 1500, 2000, 2500
- Vertical axis (left): SETTLEMENT DUE TO COMPACTION OF ORGANIC MATERIAL (feet), scale 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50

Handwritten notes at left:
- 1.56'
- 3.44'
- 6.0'
- 13.8'
- 15.7'

Curve labels (THICKNESS OF ORGANIC MATERIAL IN FEET): 0, 10, 20, 30, 40, 50

Legend:
- IO-THICKNESS OF ORGANIC MATERIAL IN FEET
- $\delta_m = 110$ lbs/ft^3
- $\delta_b = 50$ lbs/ft^3

SETTLEMENT OF FILLS PLACED ON ORGANIC MATERIAL

FIGURE 6

Y-axis (FRACTION OF TOTAL SETTLEMENT): 0, 1/4, 1/2, 3/4, 9/10, 1

X-axis (TIME IN YEARS): 0, 20, 40, 60, 80, 100, 120, 140, 160

Curve reference points: 7 YEARS, 18 YEARS, 42 YEARS, 86 YEARS, 150 YEARS

FRACTIONAL RATE
OF SETTLEMENT

TOTAL LEVEE SETTLEMENT, L (ft) — vertical axis, marked 0, 10, 20, 30, 40, 50

TIME PERIOD SINCE LEVEE COMPLETED, T (YEARS) — horizontal axis, marked 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140

I_0 - ORIGINAL THICKNESS OF ORGANIC MATERIAL IN FEET (I_i)

Curves labeled: 50, 40, 30, 20, 10, 0

EXAMPLE: FIND TOTAL LEVEE SETTLEMENT ON BOULDIN ISLAND FROM RECLAMATION TO 1987.

FROM FIGURE 4-5, I_i = 40 ft.

FROM TABLE 4-1, RECLAMATION 1910.
IN 1987 TIME PERIOD, T = 1987-1910 = 77 yrs.

FROM BELOW
ENTER T = 77 yrs
EXTEND LINE VERTICALLY TO I = 40 ft,
EXTEND LINE HORIZONTALLY TO READ
L_s = 29 ft

FIGURE 8

RATE OF SETTLEMENT, R_C (ft/yr)

TIME PERIOD SINCE ISLAND COMPLETED, T (YEARS)

IO - ORIGINAL THICKNESS
OF ORGANIC MATERIAL
IN FEET (t_i)

EXAMPLE: FIND THE SETTLEMENT THAT OCCURED ON BOULDIN
LEEVE FROM 1984-1989.

FROM FIGURE 4-5, t_i = 40 ft.

FROM FIGURE 4-1, RECLAMATION 1910.
IN 1984 TIME PERIOD, T = 1984-1910 = 74 yrs.
IN 1989 TIME PERIOD, T = 1989-1910 = 79 yrs.

FROM BELOW
ENTER T = 74 yrs (OR 79 yrs) EXTEND LINE VERTICALLY
TO t_i = 40 ft, EXTEND LINE HORIZONTALLY TO READ
R_c = 0.100 ft/yr (OR 0.090 ft/yr).

$\delta_s = \bar{R}_c \times$ TIME = ((0.090 + 0.100)/2) × 5 = 0.475 ft = 5.6 in

SACRAMENTO - SAN JOAQUIN, DELTA

SPECIAL STUDY

APPENDIX B

JANUARY 1993   Figure 4-10
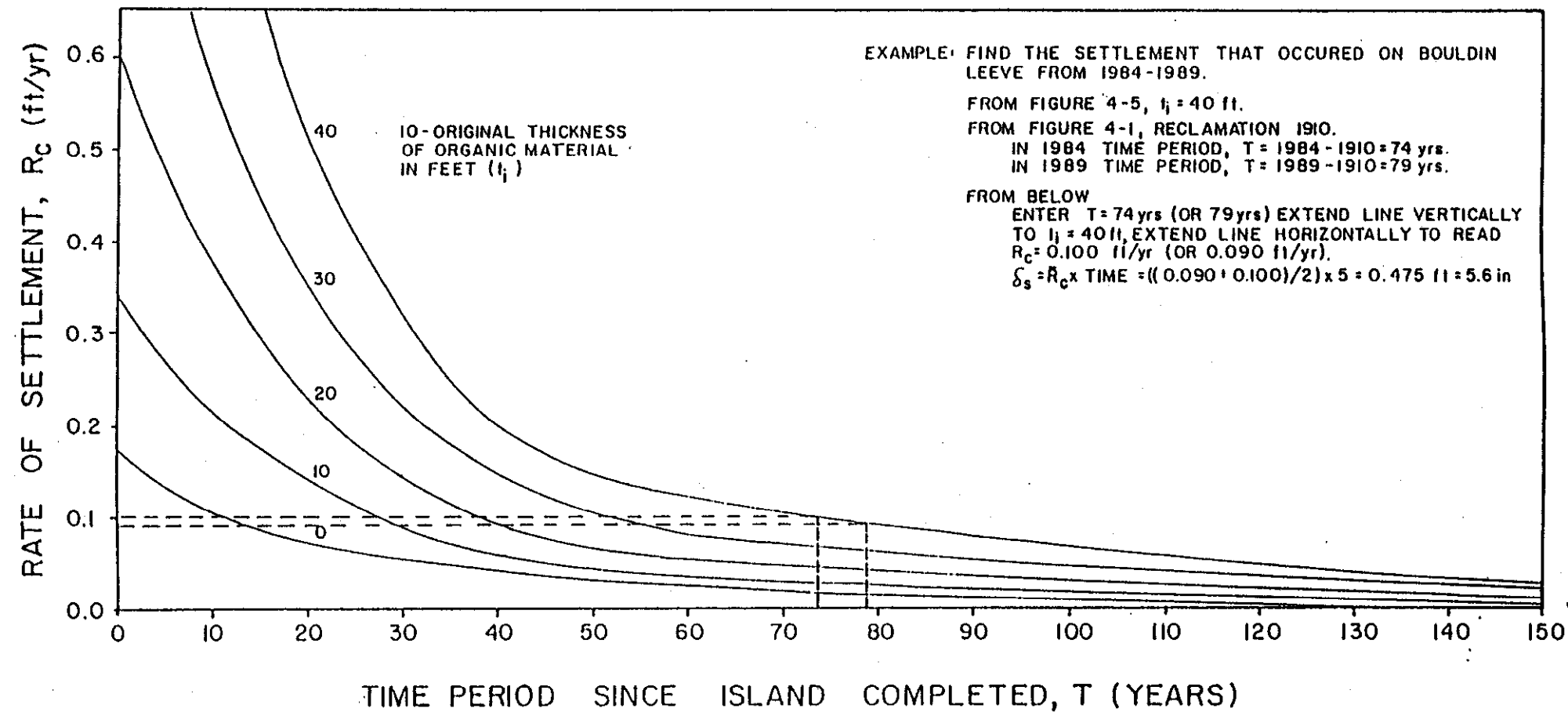
SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

Prepared for the CALFED Bay-Delta Program

by

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Hydrofocus, Inc.
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SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

Executive Summary

Subsidence on Delta islands crosses the boundaries of three of the CALFED common programs, Water Quality, Ecosystem Restoration and Levee System Integrity. Consistent with the CALFED values of integration, synergy and developing equitable solutions, subsidence mitigation needs to be addressed comprehensively. Island subsidence merits attention, future study and mitigation because of its relation to ecosystem restoration, Delta water quality, levee stability and seepage onto islands from Delta channels.

Subsidence of peat soils on Delta islands has caused the land-surface elevations to decrease since the islands were initially drained for agriculture in the late 1800's and early 1900's. The land-surface elevations of islands where peat was once present or where peat is present today range from 5 to over 20 feet below sea level. The peat soils have historically subsided at rates ranging from 0.5 to 4.5 inches per year but subsidence rates have decreased in recent years. The decreasing land-surface elevations have resulted in a decrease in the landmass resisting the hydraulic pressures on the levees and levees have been enlarged and strengthened over time. As the result of subsidence and other factors, levee failure and flooding of islands have occurred frequently since the early 1900's. A long-term approach to subsidence mitigation needs to consider a combination of non-structural and structural alternatives for managing and reversing the effects of subsidence and integrating these efforts with ecosystem restoration.

Management and reversal of the effects of subsidence in the Delta is necessary to achieve CALFED's ecosystem restoration objectives. Ecological connectivity is important for migratory fish species in the Delta, but the current lack of connectivity between Suisun Marsh west of the Delta and riparian riverine habitat east of the Delta may limit the restoration of these species. Steve Johnson of The Nature Conservancy in 1997 said: "From an ecological perspective, there needs to be tidal freshwater wetlands covering the full range of ecosystem gradients in the Delta, not just a few points here and there with the rest of the tidal wetlands hugging the shores of the eastern Delta. To achieve this range, elevations need to be restored on western Delta islands so that they can be brought back into tidal circulation." Long-term reversal of the effects of subsidence in the Delta combined with habitat restoration will be necessary to restore connectivity across the entire Delta.

Mitigation and reversal of the effects of interior-island subsidence is necessary to minimize the consequences of levee failure over the long term. Probabilistic analysis developed by the CALFED seismic hazard team suggest that levee failure is inevitable over the long-term regardless of plans to upgrade levees to PL-99 standards. The consequences and costs of levee failure and island flooding will be proportional to the depth of interior-island subsidence.

Water quality degradation in the Delta channel waters can result from levee failure in the western Delta during periods of low flow, as in the example of the flooding of Brannan and Andrus islands in 1972. This flooding required substantial operational changes in the State and Federal water projects to reestablish the hydraulic balance and compensate for salt-water intrusion. Continued subsidence on western Delta islands where there remains 10 to 60 feet of peat, will increase the volume of water that is drawn onto flooded islands thus increasing salt water intrusion and the need for dilution releases from the State and Federal water projects. For example, an average additional foot of subsidence on Sherman Island (at the rate of 0.5 inch per year this will occur in 24 years) would create about 9,900 acre feet of additional volume below sea level. This additional volume of water could be drawn from the west during flooding and could increase reclamation costs. Repairs and upgrades of Delta levees can cost from several tens of thousands of dollars to over 1 million dollars per mile.

Seepage onto Delta islands will increase as the difference in the water level in the channel and the groundwater level on the islands increases due to continued subsidence and deepening of drainage ditches. Increased seepage may require increased volumes of drainage to be pumped from Delta islands and increased pumping capacity and pumping costs. Increased drainage volumes may lead to increased loading of dissolved organic carbon to Delta channels. Increased seepage may also detrimentally affect levee stability.

The objectives of this report are to summarize the current knowledge of the causes, rates and effects of subsidence, to present the information about non-structural alternatives for stopping and reversing the effects of subsidence and to recommend directions for future research and data collection. The approach was to 1) review and summarize the available literature, 2) determine the relative magnitude of the different causes of subsidence using the available data, 3) use the areal distribution of historic subsidence rates and peat thickness to delineate priority areas for subsidence mitigation and future study and 4) determine and describe possible mitigation measures and future data collection efforts.

Consistent with the May, 1997 Governor's Flood Emergency Action Team Report that recommended that "proactive nonstructural floodplain management strategies…be implemented to reduce future flood loss and curtail the spiraling cost of State and Federal disaster assistance", this report describes non-structural options for subsidence mitigation. This report is a first step towards implementation of subsidence mitigation measures on Delta islands. The focus is the subsidence of peat soils on Delta islands. Levee subsidence that occurs primarily as the result of consolidation of organic materials underlying levees is described in another report that focuses on levee integrity.

The results of the analyses presented here indicate that present-day subsidence in the Sacramento-San Joaquin Delta is primarily the result of microbial oxidation of the peat soils. The peat soils contain a complex mass of carbon that microbes such as bacteria and fungi use as an energy source thus oxidizing the carbon to carbon dioxide gas. The available data indicate that historically, microbial oxidation caused 29 to 55 percent, consolidation and shrinkage caused 22 to 29 percent, wind erosion caused 3 to 34 percent and burning caused 9 to 24 percent of the total subsidence that occurred from the late

1800's through the 1970's. Consolidation continues to occur as the elevations of drainage ditches are lowered in response to subsidence due to microbial oxidation. Burning and wind erosion no longer appear to be significant causes of subsidence.

This report summarizes the data for changing land- and water-management practices for stopping and reversing the effects of subsidence of the peat soils. The results of research conducted by the USGS in cooperation with DWR on Twitchell Island indicate that seasonal wetlands in which the land is flooded during the fall and winter and drained in the spring and summer will not stop subsidence or reverse its effects. The primary cause of subsidence is carbon loss due to microbial oxidation of the peat. This oxidation is highest during the spring and summer. In general, land- and water management practices that result in drained and oxidized conditions during the spring and summer will result in a net carbon loss and continued subsidence. In contrast, permanent shallow flooding to a depth of about one foot resulted in a net accumulation of carbon which lead to the accumulation of biomass. The results of coring in the experimental flooded pond showed that about 3 to 6 inches of firm biomass accreted from 1993 to 1997 during 2 years of growth under full vegetative cover and 2 years of growth under partial vegetative cover. Capping of the peat with mineral material in the laboratory reduced carbon loss from the peat.

A Geographic Information System developed and housed at the Department of Water Resources Central District and available data for subsidence rates and peat thickness were used to delineate priority areas for subsidence mitigation. Figure 2 shows the location of the priority areas. There are about 23,000 acres in first priority area that includes lands where time-averaged subsidence rates from the early 1900's to the mid-1970's were 1.5 inch per year or greater and the peat is greater than 10 feet thick. There are about 36,000 acres in the priority 2 area that includes lands where time-averaged subsidence rates were greater than 1.5 inch per year and the peat is equal to or less than 10 feet thick. Lands in the priority 1 area are generally located in the central and central-western Delta where there is relatively deep peat and time-averaged subsidence rates have been generally high. Large tracts of land in the western Delta are also included in the priority 1 area. Most of the lands in the priority 2 area are in the central and central-eastern Delta where there have historically been high rates of subsidence but the peat thickness is generally less than 10 feet.

The error in the determination of areas in each priority varies depending on the magnitude of the time-averaged subsidence rate and the error in the peat thickness data. Where time-averaged subsidence rates were generally greater than 1.5 to 2 inches per year, the possible error in the delineation of the priority areas appears to be low. Where time-averaged subsidence rates are less than or equal to 1.5 inch per year, the error can be large. The peat thickness estimates can be in error due to lack of data for specific areas and because the data are based on land surface elevation data that are over 20 years old. The possible error in the delineation of priority areas for subsidence mitigation and slowing of subsidence rates in recent years points to the need for data collection to determine the present-day magnitude and areal distribution of subsidence rates.

The delineation of priority areas for subsidence mitigation is a first step towards implementation, designed to identify areas where future research and data collection efforts are needed. There is still much to be learned about subsidence, subsidence mitigation and the effects of subsidence. A comprehensive CALFED program is needed to effectively conduct and integrate future subsidence mitigation efforts. Additional data collection and research are required to:

- quantify and predict present-day and future subsidence rates,
- determine the present-day areal distribution of peat thickness,
- refine the delineation of priority areas for subsidence mitigation,
- temporally and spatially define the effects of subsidence on levee stability,
- determine the influence of future subsidence on levee foundation deformation and seepage through levees,
- determine the effects of continuing subsidence on future land use,
- determine the effects of future land subsidence on drainage water quality in Delta channels and seepage onto islands,
- develop land- and water-management practices for stopping and reversing the effects of subsidence and
- integrate subsidence mitigation into ecosystem restoration efforts.

This report resulted from a cooperative effort among the Department of Water Resources Central District (DWR), U.S. Geological Survey (USGS), the CALFED Bay-Delta Program and HydroFocus, Inc. DWR funded the majority of the data analysis and data collection described in this report related to the causes of subsidence, delineation of priority areas for subsidence mitigation and development of options for stopping and reversing the effects of subsidence. USGS provided partial funding for data collection and analysis related to the development of options for stopping and reversing the effects of subsidence and provided comments on this report. CALFED provided the majority of the funds for the writing of this report. Hydrofocus, Inc. donated time and materials for the writing of this report. The Natural Heritage Institute also provided comments on the report.

SUBSIDENCE MITIGATION IN THE
SACRAMENTO-SAN JOAQUIN DELTA

1.0 Introduction and Background

Prior to 1850, the Sacramento-San Joaquin Delta was a tidal wetland. The Delta was drained for agriculture in the late 1800's and early 1900's (Thompson, 1957). The organic or peat deposits of the Delta formed during the past 7,000 to 11,000 years from decaying plants at the confluence of the Sacramento and San Joaquin Rivers (Atwater, 1982 and Schlemon and Begg, 1975). The drained peat soils on over 60 islands and tracts are highly valued for their agricultural productivity and have undergone continuous subsidence since they were initially drained[1]. A network of levees protects the island surfaces that range from 5 to over 20 feet below sea level, from inundation.

Drainage of the Delta islands was essentially complete by the 1930's when the Delta assumed its present configuration of the islands and tracts surrounded by 1,100 miles of man-made levees and 675 miles of channels and sloughs. When most of the original levees were constructed on foundations of sand, peat and organic sediments, the difference between the water level in the channels and island surfaces was less than 5 feet. Because of the decreasing island-surface elevations due to subsidence, there has been a decrease in the landmass resisting the hydraulic pressures on the levees and the levees have been enlarged and strengthened over time.

As the result of subsidence and other factors, levee failure and flooding of islands has occurred since the early 1900's. Prokopovitch (1985) reviewed the history, causes and costs of flooding of Delta islands since the early 1900's and the information in this and the following paragraph was excerpted from pages 409-410 of his journal article. Island flooding in the early 1900's resulted mainly from overtopping of levees during high tides or spring and winter flooding. With the flood control provided by the construction of the Central Valley Project in the 1940's, overtopping became less of a factor and levee foundation instability increasingly became an important factor in island flooding. Over 50 islands or tracts have flooded since 1930.

The data for cost of levee failures and flood damage are incomplete. However, as an example, the cost associated with 11 of the 28 islands that flooded from 1969 to 1983 was about $177 million. Levee failure and island flooding can result in loss of agricultural, commercial, industrial and residential property, recreational use, communication lines and storage and transport of electricity and natural gas. The cost for levee maintenance, upgrades and repair generally ranges from several tens of thousands to over 1 million dollars per mile. Subsidence contributes to the need for levee upgrades

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[1] Subsidence is defined here as the decrease of land surface elevation. Subsidence in this report refers to the decrease in land surface elevation on the areas of the islands and tracts on the land side of the levees and is different from the lowering of the levee surface as the result of compaction of foundation materials.

and maintenance. Subsidence mitigation needs to be an integral part of any plan to prevent future flooding of Delta islands.

The cited causes of land subsidence in the Delta include aerobic microbial oxidation of soil organic carbon or microbial oxidation, anaerobic decomposition, consolidation, shrinkage, wind erosion, gas, water and oil withdrawal and dissolution of soil organic matter (Prokopovitch, 1985, Department of Water Resources, 1980; Weir, 1950). Stephens and others (1984) identified 6 causes of subsidence in drained organic soils worldwide; shrinkage due to desiccation, consolidation, compaction as the result of tillage, wind and water erosion, burning and microbial oxidation. Stephens and others (1984) reported that 53 percent of historical subsidence in organic soils in the Florida Everglades was due to microbial oxidation. Schothorst (1977) computed the percentage of the different causes of subsidence in organic soils in the Netherlands to be compaction, 28 percent; shrinkage, 20 percent; and microbial oxidation, 52 percent. The relative percentage of the different causes of subsidence in Delta have heretofore have not been quantified.

1.1 Purpose, Scope and Approach

To effectively mitigate the effects of subsidence in the Delta, the effects, rates and causes of subsidence and methods for stopping or reversing the effects of subsidence need to be identified and quantified. This report 1) summarizes information about the effects, causes and rates of subsidence, and 2) presents information about and recommendations for subsidence mitigation and future data collection.

The approach was to 1) review, synthesize and summarize the available literature and available research results, 2) estimate the relative magnitude of the different causes of subsidence using the available data, 3) use the areal distribution of historic subsidence rates and peat thickness to delineate priority areas for subsidence mitigation and future study and 4) determine and describe mitigation measures and future data collection efforts.

The overall approach for estimating the relative magnitude of the causes of subsidence was to use a computer model to synthesize and integrate the available data for subsidence rates and causes. The model estimated the amount of yearly subsidence due to different causes based on available data. The model results were compared with measured elevation change for five islands; Jersey, Sherman, Bacon and Mildred Islands and Lower Jones Tract.

The approach for the delineation of priority areas for subsidence mitigation was to use a geographic information system (GIS) developed by the Department of Water Resources Central District to analyze available data for the Delta for subsidence rates, depth of peat soils and soil characteristics. The Department of Water Resources (1980) mapped the islands of greatest subsidence and listed the peat thickness for each island. The *representation of the areal distribution of subsidence rates and peat thickness presented* here is an improvement relative to the previous effort (Department of Water Resources,

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1980) because 1) the error in the estimated subsidence rate is generally lower, quantifiable and the result of temporally uniform elevation change determinations, and 2) the estimates for peat thickness are based on more recent and comprehensive data. Also, the data was entered into a GIS which facilitated the evaluation of the data for delineation of priority areas in greater areal detail than entire islands such as generally presented in Department of Water Resources (1980).

2.0 Methodology

2.1 Methodology for Estimating the Relative Magnitudes of the Causes of Subsidence

A computer model was developed to estimate yearly subsidence. The simulated causes of subsidence were aerobic microbial oxidation of organic carbon, consolidation and shrinkage, wind erosion, burning and withdrawal of natural gas and groundwater. Subsidence due to aqueous carbon loss was not simulated because data presented by Deverel and Rojstaczer (1996) indicated that it accounts for less than 1 percent of the measured subsidence. Data presented in Deverel and others (1998) indicated that anaerobic decomposition of Delta organic soils is small relative to other causes of subsidence and was also not included in the model. The data and methodology for simulating the causes of subsidence are summarized here and are described in detail in Appendix A.

2.1.1 Microbial Oxidation

The carbon flux data for Jersey Island collected from 1990 to 1992 (Deverel and Rojstaczer, 1996) was used to approximate the relation of microbial oxidation of organic carbon to soil organic carbon content. This relation was then used to simulate subsidence due to microbial oxidation for Jersey Island at the study location of Deverel and Rojstaczer (1996). The mass of carbon lost by microbial oxidation was assumed to follow Michaelis-Menton kinetics (Conn and Stumpf, 1976). In the Michaelis-Menton equation, the amount of carbon loss due to microbial oxidation is proportional to the amount of organic carbon in the soil.

2.1.2 Consolidation and Shrinkage

When the organic soils of the Delta were initially drained, there was substantial consolidation and shrinkage due to water loss. There is also annual consolidation that is a result of an effective stress on the peat material near the water table. As the soil subsides and oxidizes, the elevation of the bottom of drainage ditches is decreased to lower the water table thus decreasing the buoyant force of water supporting the peat. There is also an increase in loading due to the increasing density of the oxidizing soil. Shrinkage may also cause a loss in volume as the peat soils are dried but this has not been well quantified in the Delta. This annual subsidence due to consolidation was simulated in the model as equal to the volume of water lost when the water table is lowered. The amount of initial

shrinkage and consolidation during reclamation was estimated from an empirical equation presented in Eggelsmann and others (1990).

2.1.3 Wind Erosion

Wind erosion of peat soils caused dust storms that affected Stockton, Lodi and Tracy prior to the early 1960's (Alan Carlton, former University of California Extension Specialist for the Delta, personal communication, 1997). The prevailing westerly winds of oceanic air masses moving to the Central Valley caused dust storms primarily during May and June (Schultz and Carlton, 1959; Schultz and others, 1963). There are few reported values of annual amounts of peat soil eroded by wind that range from 0.1 to 0.57 inch per year (Department of Water Resources, 1980; Carlton, 1965).

Crop histories in Thompson (1958) and the Weir transect notes (see Rojstaczer and others, 1991) were used to determined the spatial distribution of crops grown on the islands where land surface elevation changes were simulated. Wind erosion was calculated at varying rates of 0.1 to 0.57 inch per year where asparagus was grown or where the land was fallow. There was generally a shift from the planting of asparagus and other vegetable crops to corn in the Delta in the 1950's and 1960's and the model calculated minimal wind erosion after 1965.

2.1.4 Burning

Weir (1950) and Cosby (1941) estimated that the peat soils were burned once every 5 to 10 years. Data analysis in Rojstaczer and Deverel (1995) and Rojstaczer and others (1991) indicated that burning occurred more frequently during World War II when potatoes were grown extensively. Burning was used to control weeds and diseases and to create ash for potatoes. Weir (1950) stated that 3 to 5 inches of peat were typically lost during a single burning. Burning was simulated differently for the islands depending on the distribution of crops following the information presented in Cosby (1941) and Weir (1950).

2.1.5 Withdrawal of Natural Gas

Since the discovery of the Rio Vista Gas field in the 1930's, several natural gas fields have been developed in the Delta. Compaction of the sediments could occur if the gas reservoirs were substantially depressurized which could result in subsidence of Delta islands. To determine the subsidence due to natural gas withdrawal, sediment cores collected from channel islands were dated by determining the levels of cesium-137 at 1-inch depth intervals (Rojstaczer and others, 1991). Records from the California Department of Conservation, Division of Oil and Gas, indicate that gas production began to increase substantially in the mid-1950's and gas withdrawal was simulated as a contributor to subsidence in the model after 1955.

2.1.6 Simulation of Total Subsidence

The total annual depth of subsidence was estimated by summing the depths of subsidence due to the different causes for each yearly time step. The model accreted the land surface as it progressed backward in time based on the mathematical representation of the causes of subsidence. The soil organic carbon content and bulk density were estimated for the most recent elevation data and were recalculated for each subsequent time step. Subsidence and the microbial oxidation of organic carbon were simulated as a two-layer process based on data presented by Carlton (1966). The soil organic matter content was recalculated for each layer at each time step based on the simulated change in the total mass of carbon for each layer.

2.2 Methodology for Delineation of Priority Areas for Subsidence Mitigation

The delineation of priority areas for subsidence mitigation in the Delta is based on the areal distribution of historical, time-averaged subsidence rates calculated from the early 1900's to the mid-1970's and peat thickness. The first priority area was chosen to include those lands where the time-averaged subsidence rates were high (greater than 1.5 inch per year) and where there is still substantial peat (greater than 10 feet) remaining. The second priority area was chosen to include those areas where the time-averaged subsidence rates were high (greater than 1.5 inch per year) but there was 10 feet or less of peat remaining. It was assumed that the distribution of time-averaged subsidence rates generally reflects the relative distribution of present-day subsidence rates. Areas where time-averaged subsidence rates were lower than 1.5 inch per year were not considered to be high priority areas for immediate subsidence mitigation. A Geographic Information System for the Delta developed by, and housed at the Department of Water Resources Central District was used for the delineation of priority areas. The methodology used is summarized here and described in detail in Appendix B.

Two sets of US Geological Survey topographic maps were used to estimate the time-averaged rates of subsidence throughout the Delta from the early 1900's to 1974 through 1978. The difference in elevation between the two time periods was estimated to be the total depth of subsidence. The time-averaged rate of subsidence was calculated as the total amount of subsidence divided by the time interval that ranged from 60 to 72 years. The error in the subsidence rate estimate results from the error in the elevation estimate from the topographic maps and the change in mean sea level datum from the early 1900's to 1976 to 1978. The methodology for estimating the error associated with the time-averaged subsidence rate is described in Appendix B.

The peat thickness was calculated as the difference between the basal elevation of peat and peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps. Atwater's (1982) peat and peaty mud of tidal wetlands include the organic deposits derived from decayed vegetation that formed during the sea level rise during the last 7,000 years. Atwater's (1982) delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soil surveys.

The peat thickness data was compared with the delineation of organic soils or highly organic mineral soils in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993). Where there were discrepancies between the two sources of information for the extent of peat soils, the soil survey data was assumed to be correct.

The delineation of soil series as mapped in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993) were entered in digital form into the GIS developed by the Department of Water Resources Central District. The soil organic matter content was the primary soil characteristic of interest. The soil organic matter content was estimated for the 11 soil series which were either organic soils or highly organic mineral soils based on the data provided in the soil surveys.

3.0 Effects of Subsidence

Levee stability is directly affected by continued subsidence within a zone of influence adjacent to levees. The spatial and temporal definitions of the zone of influence have not been quantified for the Delta and are site specific. The temporal and spatial definitions of the zone of influence should be based on analysis of the effects of future subsidence primarily on seepage and deformation of levee foundations. Deformation analysis (e.g. Foote and Sisson, 1992) of Delta levees heretofore have not considered the effects of future subsidence.

Seepage onto Delta islands will increase due to future subsidence. As the water level on the island is lowered as the result in increased drainage depth, the hydraulic gradient from the water surface in the channel to the groundwater in the interior of the island will increase. This will in turn increase the rate of seepage onto the island and may affect seepage through the levee and the erosion of foundation materials. Future data collection and analysis are needed to determine these effects.

Seepage onto Delta islands is removed, along with agricultural return flows, through a network of drainage ditches and one or more drainage pumps that pump drainage water from the islands into the channels. Templin and Cherry (1997) quantified the volume of drainage water pumped from Delta islands in 1995. Their data indicate that volumes of drainage water ranged from 2 to 4 acre-feet per acre in the central and western Delta. As a point of reference, average reference evapotranspiration for the Delta (Orang and others, 1995) is about 4.5 feet. Actual consumptive use of water by crops is less than reference evapotranspiration. About 260 agricultural drains discharge and contribute to high dissolved organic carbon (DOC) loading into the Delta channels as the result of leaching of the organic soils (Department of Water Resources Municipal Water Quality Investigations Program, 1997). High DOC concentrations can result in unacceptably high concentrations of disinfection byproducts when the water is treated for drinking. Because of increasing seepage volumes, drainage loads for DOC and disinfection byproducts may increase with increasing subsidence.

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Unintentional flooding of Delta islands as the result of levee failures can cause additional water quality degradation due to salinity intrusion. Past subsidence has resulted in reduced landmass to support levees and continued subsidence can exacerbate the water quality effects of flooding by increasing the volume of water that will move onto the island during flooding. Cook and Coleman (1973) described the effects of flooding of Andrus and Brannan islands in June 1972. The Brannan-Andrus flooding is the only documented example of water quality degradation as the result of island flooding. The water balance in the Delta was upset as the result of the levee failure as 150,000 acre-feet of water moved onto the islands that in turn resulted in the movement of salt water from the west into the Delta. State and Federal exports of water from the Delta were temporarily reduced and releases from Central Valley Project reservoirs were increased to reduce the salinity intrusion. The total cost of the flooding was $22.5 million. Three hundred thousand acre-feet of additional water were released from storage from State and Federal water projects.

Short-term water quality problems probably would not occur if breaks occur during winter periods of high flow. Nor do water quality problems occur with all flooding during periods of low flow. The extent of water quality degradation is dependent on the location of the flooding and the flow conditions. Island flooding in the western Delta during low flow periods is the primary concern. Several of the western Delta islands have depths of 10 to 60 feet of peat remaining and continued subsidence will increase the volume of water that will move onto the island during flooding. For example, on Sherman Island an additional foot of subsidence over the entire island during the next 24 years (0.5 inch per year) will result in an additional volume of 9,900 acre-feet below sea level that can move onto the island during flooding. Probabilistic analysis developed by the CALFED seismic hazard team suggest that levee failure is inevitable over the long-term regardless of plans to upgrade levees to PL-99 standards. The consequences and costs of levee failure and island flooding will be proportional to the depth of interior-island subsidence.

4.0 Rates and Causes of Subsidence

4.1 Rates of Subsidence

Cited historic and time-averaged rates of subsidence in the Delta range from about 0.5 to 4.6 inches per year (Rojstazcer and others, 1991; Prokopovich, 1985, Department of Water Resources, 1980). Department of Water Resources (1980, p. 1) stated that estimates of subsidence for the years 1911 to 1952 were 3.0 inches per year on 17 Delta Islands or tracts. Department of Water Resources (1980) also listed the total amount of subsidence for 21 islands as ranging from 10 to 21 feet and time-averaged rates ranging from 1 to 4.6 inches per year. Prokopovitch (1985, p. 405) reported the same range for time-averaged subsidence rates. Rojstaczer and others (1991) evaluated subsidence from changes in land-surface elevations against power pole foundations installed in 1910 and 1952 in 1987 on Sherman and Jersey Islands. The time-averaged subsidence rate from 1910 to 1987 ranged from 0.5 to 1.2 inch per year. The time-averaged subsidence rate from 1952 to 1987 ranged from less than 0.3 to 0.7 inch per year. This and information presented by Rojstaczer and Deverel (1993) indicate that subsidence rates have slowed in recent years.

Rojstaczer and Deverel (1993) determined that a logarithmic expression for the decrease in the land-surface elevation over time statistically fit the data best for Bacon and Midlred islands and Lower Jones Tract where the time averaged historic subsidence rates were 2 and 3 inches per year from 1924 to 1981. The estimates for subsidence rates in 1980 for these three islands ranged from 1.2 to 1.6 inch per year (Rojstaczer and Deverel, 1993). Subsidence rates are slowing for two reasons. First, the rate of microbial oxidation is proportional to the amount of organic carbon in the soil which is decreasing with time. Second, other factors such as wind erosion and burning contributed to subsidence in the past but do not appear to contribute significantly to present-day subsidence. Deverel and Rojstaczer (1996) continuously measured present-day subsidence rates from 1990 to 1992 by on Sherman and Jersey Islands and Orwood Tract. These authors reported rates of 0.2, 0.24 and 0.32 inch per year on Sherman, Jersey and Orwood, respectively.

4.2 Causes of Subsidence

4.2.1 Simulation Results

Table 1 shows the range of simulated elevation changes and percentages of the total subsidence due to the different causes. The results in Table 1 for the different simulations reflect variations in the amount of wind erosion for all the islands and the parameters in the Michaelis-Menton equation for microbial oxidation.

Table 1. Simulated changes in elevation and causes of subsidence for Jersey, Sherman, Mildred and Bacon islands and Lower Jones Tract.

| Island (years of simulation)	Simulated changes in elevation (in feet)	Measured change in elevation (in feet)	Simulated range in percent of total subsidence due to:				
			Microb-ial oxida-tion	Consoli-dation and shrinkage	Wind erosion	Burning	Gas with-drawal
Jersey (1886 –1975)	5.3 – 8.1	6.7 +/- 2.5	31 – 48	22 – 25	11 –26	9 – 13	2 – 3
Sherman (1910 – 1987)	4.7 – 6.05	6.0 +/- 1.0	29– 47	24 – 25	9 – 34	10 – 14	
Mildred (1924 – 1981)	10.8 – 11.4	11.6 +/- 2.0	37 – 50	29 – 30	3 – 17	18 –19	
Bacon (1924 – 1978)	10.5 – 11.0	10.5 +/- 1.0	36 – 49	24 – 25	3 – 17	23 – 24	
Lower Jones (1924 – 1981)	10.0 – 10.4	9.45 +/- 1.5	41 - 55	24 – 25	3 – 18	18 - 19	
Total range	-	-	29 – 55	22 – 29	3 – 34	10 - 24	2 - 3

The most recent elevation data for Jersey Island in Table 1 is from the 1978 topographic map that shows topography from photogrammetric methods using aerial photos conducted in 1974 and plane table elevation data collected in 1976. Thompson (1957) indicated that Jersey Island was initially drained in 1886. The measured elevations for Sherman Island in Table 1 were from elevations determined in 1988 against power pole foundations installed in 1910 (Rojstaczer and others, 1991; Rojstaczer and Deverel, 1995). The estimated error for the Sherman data was about 1 foot (Rojstaczer and others, 1991). The estimated error in the Jersey elevation change is about 2.5 feet. The measured changes for Mildred, Bacon and Lower Jones were from the leveling data collected along the Weir transect (Weir, 1950) by University of California personnel (see Rojsatczer and others, 1991).

Table 1 shows that the primary causes of historical subsidence simulated on the five islands are microbial oxidation of organic carbon (29 to 55 %) and consolidation and shrinkage (22 to 29 %). Much of the consolidation for Jersey and Mildred islands occurred when these islands were initially drained. This accounts for the relatively large percentage of total simulated subsidence due to consolidation for these islands. The Jersey Island simulation extends from the approximate year of initial drainage to 1975 when the most recent elevation data was collected. The Mildred Island simulation extended from 1924 (the year of initial drainage) through 1981 to coincide with the leveling data reported in Rojstaczer and others (1991).

The amounts of the different causes of subsidence varied with time. Figure 1 shows the amount of subsidence contributed by the different processes for the five islands from 1886 to 1985 in 10-year intervals. Consolidation is the predominant process during the first year after initial drainage. Burning was the predominant cause in 1945. Wind

erosion and gas withdrawal are minor causes that account for less than 10 percent of the total yearly subsidence. Simulation results for 1975 on Jersey, Mildred, Bacon and Lower Jones and 1985 on Sherman indicate that present-day subsidence is caused primarily by microbial oxidation and consolidation (75 percent and 25 percent, respectively). Deverel and Rojstaczer (1996) also studied present-day subsidence from 1990 to 1992 on Jersey and Sherman Islands and Orwood Tract. Their results indicated that 60 to 76 % of the measured subsidence was due to microbial oxidation. Comparison of model results and measured elevations shown in Apendix A indicate good agreement between simulated and measured results for Mildred, Bacon and Lower Jones.

Figure 1. Subsidence rates in feet per year from 1886 to 1985 due to different causes for Jersey, Sherman, Bacon and Mildred Islands and Lower Jones Tract.
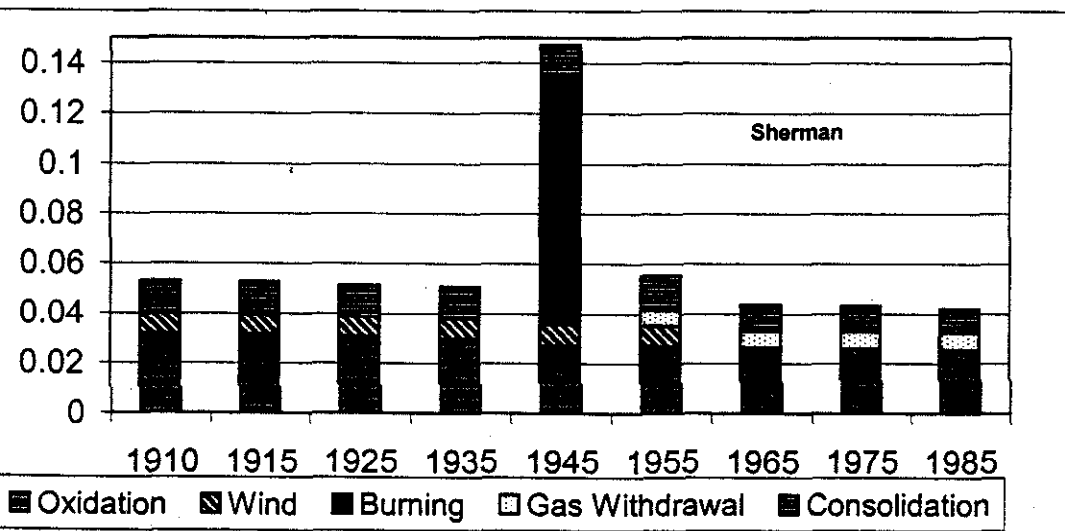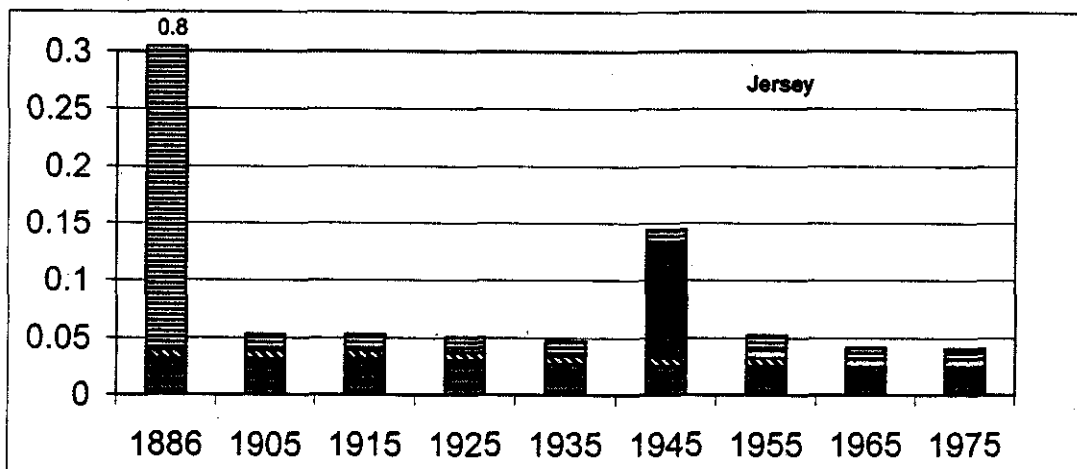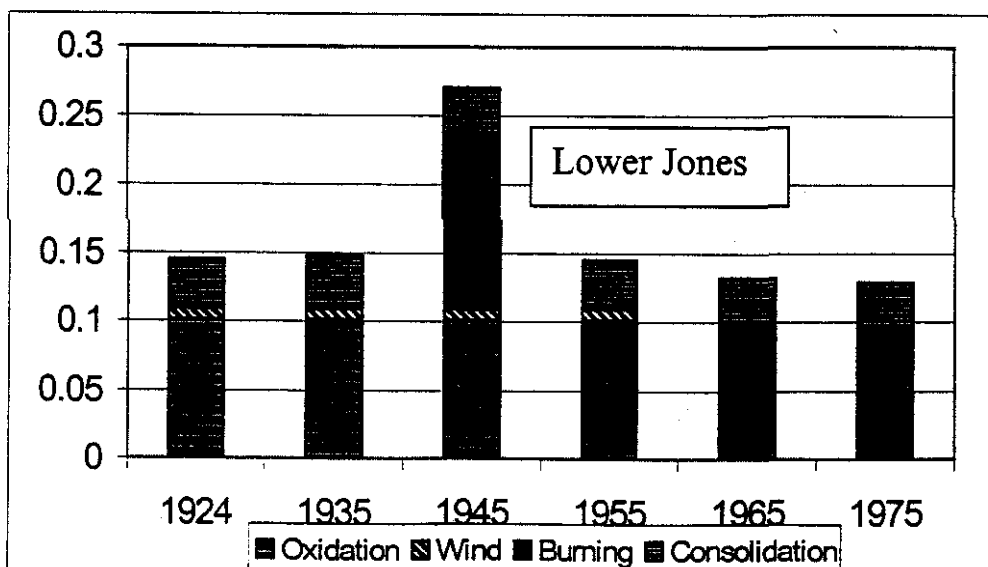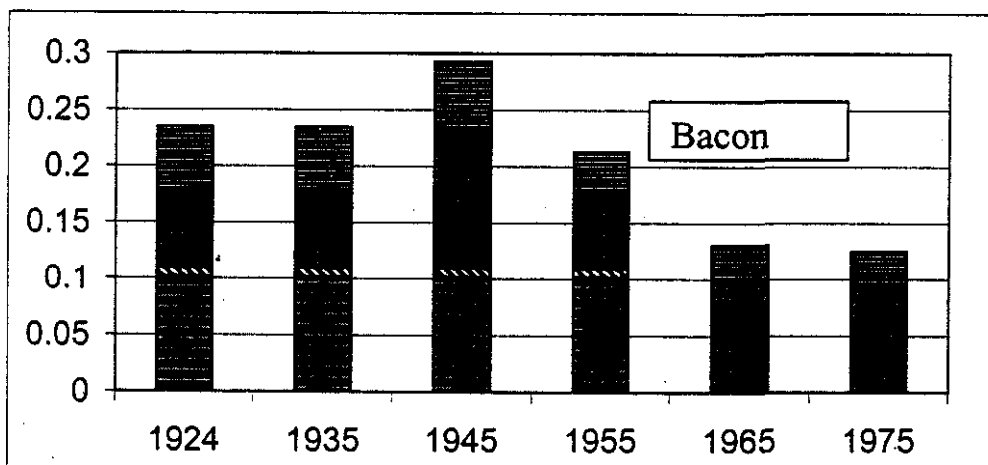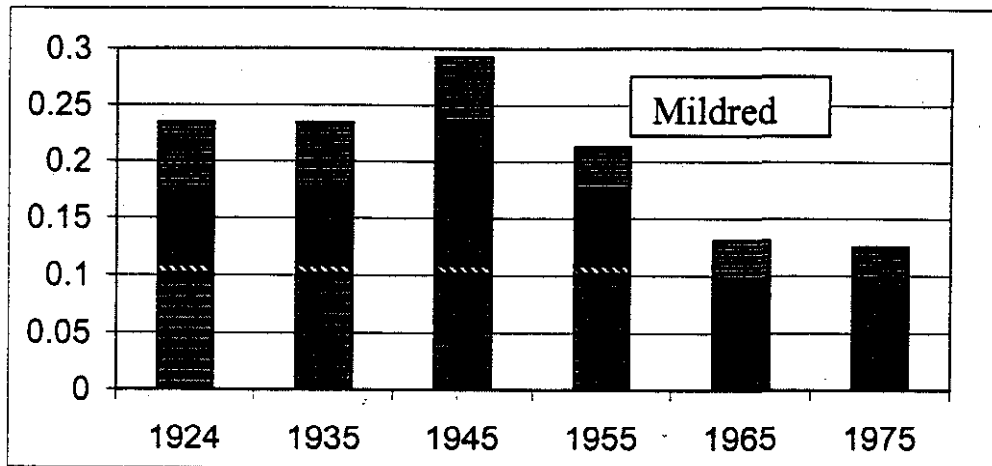
4.2.2 Limitations in the Determination of the Causes of Subsidence

Although estimates of the magnitude of the causes of subsidence are consistent with what is known about the processes affecting subsidence in the Delta, the primary limitation of the analysis is the lack of explicit and deterministic simulation of the causes of subsidence. The equation for microbial oxidation is based on limited data and does not explicitly simulate the microbial decomposition of the different components of the soil organic carbon. Consolidation during initial drainage is empirically based. Also, ongoing consolidation of the organic soil after initial drainage is simulated to be the result of water loss only. There is probably a rearrangement of the soil fabric as subsidence and decomposition proceeds that is not currently quantifiable and is not included in the model. Burning of organic soils in the Delta was not well documented and simulation of burning is based on limited data discussed in Cosby (1941) and Weir (1950). The mechanics of wind erosion are also not explicitly modeled due to lack of data. These limitations, especially as related to the simulation of microbial oxidation and consolidation, point to the need for additional data collection and research for improved understanding and prediction of subsidence rates.

5.0 Distribution of Priority Areas for Subsidence Mitigation

Figure 2 shows the distribution of the two priority areas for subsidence mitigation. The priority 1 area is comprised of lands where the peat thickness is greater than 10 feet and the time-averaged subsidence rate was greater than 1.5 inch per year. The priority 2 area is comprised of lands where the time-averaged subsidence rate was greater than 1.5 inch per year and the peat thickness is 10 feet or less. Peat thickness is generally greatest in the western and northern parts of the Delta; the largest areas of peat thickness greater than 10 feet are on Sherman, Twitchell, Brannan-Andrus, Grand, Staten and Tyler islands and Webb Tract. The amount of area in priority 1 varies among these and other islands according to the distribution of time-averaged subsidence rates. The acres for the two priority areas for the different islands are presented in Appendix B.

The largest acreage for priority 1 is on Webb Tract in the west-central Delta. Venice, Bouldin and Mandeville islands in the central Delta also have large acreage assigned to the priority 1 area. Twitchell, Brannan-Andrus and Sherman islands and Webb Tract in the western and west-central Delta and Tyler Island in the northern Delta also have large areas in this priority. Although Grand Island has a large acreage of peat thicker than 10 feet, the time averaged subsidence rates are almost all less than 1.5 inch per year. The total area for priority 1 is about 22,900 acres.

The islands with the largest acreage in the priority 2 area are in the central Delta where subsidence rates have been historically high and there are large areas of peat that are less than 10 feet thick. MacDonald, Bacon and Mandeville islands and Empire Tract in the Central Delta and Rindge Tract in east-central Delta and Webb Tract in the west-central Delta have large areas in priority 2. Other central Delta islands (Lower Jones Tract, Bouldin Island and Venice Island) have substantial areas in priority 2. The islands and tracts of the western and northern Delta generally have low acreage in the priority 2 area

Figure 2. Priority areas for subsidence mitigation in the Sacramento-San Joaquin Delta. Overlapping hatched areas represent priority 1 areas where time-averaged subsidence rates were greater than 1.5 inch per year. Priority 2 areas are encompass those lands where time-averaged subsidence rates were greater than 1.5 inch per year and peat thickness is less than or equal to 10 feet.

EXPLANATION

Subsidence rate greater than 1.5 inches per year

Peat thickness greater than 10 feet.

because of the relatively low time-averaged subsidence rates. The total area for priority 2 is about 35,700 acres. The total area for priorities 1 and 2 is about 58,600 acres.

Deverel and others (1998) reported that time-averaged subsidence rates were highly correlated with percent soil organic matter on Sherman Island. The distribution of soil organic matter content in the Delta generally reflects the distribution of subsidence rates shown in Figure 2. For example, the highest organic matter contents (greater than 30 percent) are in the central, east-central and the west-central Delta (Twitchell Island, Bradford Island, Webb Tract, Bouldin Island, Venice Island, Empire Tract, Rindge Tract, King Island, Bacon Island, Lower Jones Tract). The time-averaged subsidence rate for the majority of these islands is greater than 1.5 inch per year (Figure 2). Islands where organic matter contents are generally lower than 15 and 30 percent such as Sherman Island, Brannan-Andrus Island, Staten Island and Victoria Island are generally at the periphery of the Delta. The subsidence rates on these islands are generally less than 1.5 inch per year.

5.1 Uncertainty in the Delineation of Priority Areas

The primary uncertainties in the spatial analysis are the result of uncertainties in the thickness of the peat soil and the error in the estimation of the subsidence rate. The subsidence rate error is the result of errors associated with the use of topographic elevations as described above and the use of different datums for the 2 surveys for the topographic maps published in 1906 to 1911 and 1976 to 1978. In general, large errors in the subsidence rates correspond to areas of the lowest time-averaged subsidence rates. The error in the subsidence rate estimate due to the mapping error is 50 percent or less for much of the Delta where there are peat deposits. The error in the subsidence rate generally increases approaching the periphery of the Delta. The error in the western, eastern, southern and northern edges of the Delta generally approaches or exceeds 100 percent.

The key questions related to the error for the purpose of determining the priority areas based on time-averaged subsidence rates are: 1) Is the distribution of subsidence rates consistent with what is known about the distribution of present-day subsidence rates? and 2) What is the error associated with assignment of areas to one of the two categories (less than and greater than 1.5 inch per year) for subsidence rates?

The first question can be answered qualitatively based on recently collected data for subsidence for selected areas of the Delta. Specifically, data from Rojstaczer and Deverel (1995), Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) are consistent with the spatial distribution of subsidence rates presented here. Time-averaged subsidence rates reported for the central Delta (Lower Jones Track, Bacon and Mildred islands) are greater than in the western Delta (Sherman and Jersey islands) (Rojstaczer and others, 1991). However, subsidence has not been measured extensively throughout the Delta so that it is impossible to compare rates for all the islands. The subsidence rates in Figure 2 are generally consistent with what is known about subsidence and organic soils in the Delta (Prokopovitch, 1985). The highest soil organic matter contents and

subsidence rates are in the central Delta. The soils are lower in organic matter content and subsidence rates are lower approaching the margins of the Delta

The second question can be answered based on the distribution of error for subsidence rates. The error analysis is discussed in Appendix B. Data for Sherman Island and Webb Tract were used to evaluate the effect of errors on the acreage within each priority area. The data for these islands represent the variability in the data set and the error analysis illustrates the possible range in calculated acreage in the two priority areas.

The range of acreage on Webb Tract for priority 1 shows that the acreage in priority 1 could be overestimated by 54 % and underestimated by less than 1 %. For priority 2, the range in acreage on Webb Tract shows that the acreage in priority 2 could be overestimated by 24 % and underestimated by 10%. In contrast, the ranges of acreage in each priority for Sherman Island are large, ranging up to 1,000 percent. The time-averaged subsidence rates for Sherman were lower than Webb and therefore the error associated with the subsidence-rate estimate is higher and the range of acreage classified in each priority area is large. The results of this analysis point to a need for additional data collection for subsidence rates, especially in the western Delta.

The areal distribution of the estimation error for the peat thickness was not determined. The density of borehole data and the error in the land-surface elevation primarily determines the error. The land-surface elevation error is due to leveling error in the determination of land-surface elevation that is about plus or minus 2.5 feet and the subsidence that has occurred since 1974 (about 1 to 4 feet). The total land-surface elevation error ranges from about −1.5 to 6.5 feet.

Appendix B shows and discusses the number and average density of data points for borehole logs used to estimate the peat thickness. In general, data densities greater than 200 acres per data point result in moderate to high uncertainty in the estimation of the basal peat elevation for large areas of the islands. Of those islands where the density of peat thickness data is greater than 200 acres per data point, only 7 have acreage in the 2 priorities (Orwood Tract, Victoria Island, Brannan and Andrus islands, King Tract, Tyler Island and Grand Island). Brannan-Andrus Island, King Tract and Tyler Island have significant acreage in the 2 priorities. Grand Island is mapped as having a large area of thick peat but has little acreage in priority area 1 because of the low time-averaged subsidence rates. The percent organic matter in the soils on Grand Island is relatively low. Although there is uncertainty in the delineation of the priority areas for subsidence mitigation, the delineation is based on the available data and provides a starting point for further data collection efforts to better define areas and management practices for subsidence mitigation.

6.0 Land- and Water Management Practices for Subsidence Mitigation

The primary factor contributing to present-day subsidence in the Delta is microbial oxidation of soil organic carbon. The oxidation of soil organic carbon is directly proportional to soil temperature and decreases with increasing soil moisture (Deverel and Rojstaczer, 1996). The results of studies conducted by the US Geological Survey and

Department of Water Resources (Deverel and others, 1998) demonstrated that permanent shallow flooding reversed the effects of subsidence on Twitchell Island. Permanent shallow (about 1 foot) flooding resulted in a net carbon accumulation and accretion of biomass. The plots were first flooded in February 1993. Cattails were the primary species that colonized the plots. During 1993, the cattails covered about 25 percent of the plot. In 1994, 30 to 55 percent of the plot was covered and full vegetative cover was achieved in 1995. Cores were collected in the flooded plot while it was temporarily drained in July 1997. The results of the coring showed that about 3 to 6 inches of firm biomass accreted from 1993 to 1997 during 2 years of growth under full vegetative cover and 2 years of growth under partial cover. Other water-management strategies that were evaluated; seasonal flooding during the late fall and winter with and without irrigation during the spring and summer, resulted in a net carbon loss and are not viable mitigation strategies for stopping subsidence. This is due to large microbial oxidation rates that occur during the spring and summer.

Consistent with the potential of permanent shallow flooding to reverse the effects of subsidence, two projects are funded and one is underway to evaluate the large scale effects of this management practice. First, data collection began in October of 1997 on Twitchell Island on a 15-acres demonstration project for increasing land-surface elevation through biomass accumulation under permanently flooded conditions. The overall approach is to verify the reversal of subsidence in organic soils under permanently flooded conditions at a larger scale than used in previous research (Deverel and others, 1998). The demonstration project will provide information about: 1) the large scale effects of permanent flooding on the carbon balance and land-surface elevation changes; 2) the effects of different water-management practices and vegetation on biomass accumulation and land-surface-elevation changes; 3) the effects of varying soil organic matter content on the carbon balance under permanently flooded conditions and 4) future potential increases in land-surface elevation.

Second, a $3.5 million project has been funded through the CALFED Category 3 process to develop quantitative answers to the key unanswered questions about the reversal of the effects of subsidence and the development of tidal wetland habitat in the Sacramento-San Joaquin Delta. The focus of the project is the development of cost-effective techniques for the reversal of the effects of subsidence. This will be accomplished through research and a demonstration project for tidal wetland habitat restoration on Twitchell Island that will be transferable to other Delta islands. Quantitative answers to questions about the feasibility of depositing sediment on Delta islands and potential water quality impacts of accreting the land surface through biomass accumulation will be addressed during the conduct of this project. This project is scheduled to begin in early 1999.

Other water- and land-management strategies are being evaluated that may stop, or reverse the effects of, subsidence include capping the organic soil with mineral material and reverse wetland flooding. Preliminary results by the USGS (Lauren Hastings, USGS, personal communication, 1998) indicate that capping the unsaturated peat soil with 2 feet of dredge sand reduces the emission of carbon dioxide by about 35%. Capping of partially saturated soil reduced emission of carbon dioxide by 23%. Capping saturated

peat soil with dredge material could provide upland habitat in shallow flooded wetlands.
Capping of the peat reduces the transport of oxygen and carbon dioxide in and out of the
soil causing the rate of carbon dioxide emission to decrease.

Reverse wetland flooding involves shallow flooding during the spring and summer and
drainage during the fall and winter. This may reduce oxidation when it is usually the
greatest and result in organic matter accumulation. The USGS is currently evaluating this
as a subsidence mitigation strategy.

Subsidence mitigation efforts should be coordinated with efforts to restore the ecological
health of the Delta. From an ecological perspective, there needs to be freshwater
wetlands covering the full range of ecosystem gradients in the Delta. To achieve this
range, elevations on western Delta islands must be restored to bring some of the islands
back into tidal circulation (Steve Johnson, The Nature Conservancy, 1997).

7.0 Summary and Recommendations

7.1 Summary

- A computer model was used to integrate and synthesize the available data for the
  historic causes of subsidence in Delta organic soils. The model that simulated the
  relative magnitude of the causes of subsidence was validated using measured data for
  carbon fluxes and subsidence rates on Sherman, Jersey, Bacon, and Mildred Islands
  and Lower Jones Tract.
- The model simulations indicate that 29 to 55 percent of the total amount of historical
  subsidence on the Delta organic soils that occurred from the late 1800's through the
  1970's was due to microbial oxidation of organic carbon.
- The model simulations indicate that consolidation and shrinkage, whether initially or
  over time because of drainage, accounted for about 22 to 29 percent of the total
  historical subsidence. Burning has accounted for 9 to 24 percent of the total historical
  subsidence. Wind erosion has historically accounted for 3 to 34 percent. Gas
  withdrawal has historically accounted for less than 3 percent.
- Present-day subsidence is caused primarily by the microbial oxidation of organic
  carbon.
- Time-averaged subsidence rates and peat-thickness were used to determine priority
  areas for subsidence mitigation in the Sacramento-San Joaquin Delta.
- Two priority areas for subsidence mitigation were determined as follows. The
  priority 1 area encompasses lands where time-averaged subsidence rates were greater
  than 1.5 inch per year and peat thickness was greater than 10 feet. The priority 2 area
  encompasses lands where the subsidence rates were greater than 1.5 inch per year and
  the peat is less than or equal to 10 feet thick.
- The largest priority-1 areas are in the western, west central and central Delta. The
  total area for priority 1 is about 22,900 acres.
- The largest priority 2 areas in are in the central Delta and central-eastern Delta where
  subsidence rates have been historically high. The islands and tracts of the western
  and northern Delta generally have low acreage in priority 2 because of the low

historical subsidence rates in these areas. The total priority-2 area is about 35,700 acres.

- The total area for both priorities is about 58,600 acres.
- The uncertainty in the estimation of priorities depends on the magnitude of the time-averaged subsidence rate and the uncertainty in the estimation of the peat thickness. The error in the subsidence rate estimate is generally less than 50 percent where subsidence rates are greater than 1.5 inch per year. This primarily corresponds to areas in the central Delta. The error in the subsidence rate increases approaching the margins of the Delta.
- The error in the subsidence rate has relatively less effect in the assignment of priorities on islands where the time-averaged subsidence rates were high such as Webb Tract. However, it has a large effect on the assignment of priorities for islands such as Sherman where historical subsidence rates have been lower.
- Permanent and shallow flooding of organic soils and capping, reduce or stop subsidence rates and shallow flooding can stop or reverse of the effects of subsidence.
- The effects of continued subsidence include levee instability, increased seepage onto islands and water quality effects related to seepage and flooding.

7.2 Recommendations for Research and Additional Data Collection

Eight western Delta islands (Sherman, Jersey, Twitchell, Bradford, Holland, Hotchkiss, Bethel and Webb) encompass a key area for subsidence mitigation because of the potential for water quality deterioration as the result of a levee break on these islands during low flow. Figure 2 shows that large areas of Twitchell, Webb and Bradford are included in the first priority area. Relatively small areas of Sherman, Jersey, Bethel, Hotchkiss and Holland are included in the two priorities. However, the error analysis discussed above indicates that the uncertainty in the assignment of priority areas on Sherman Island is as large as 1,000 percent. The uncertainty on Webb Tract is small. Examination of the subsidence rates and the error in the subsidence rates for Jersey, Holland, Hotckiss and Bethel indicate that the error in the assignment of priorities for these islands is generally similar to the error for Sherman Island.

The uncertainty in the assignment of priorities points to the need for additional data for subsidence rates throughout the Delta prior to implementation of subsidence mitigation measures. Since subsidence mitigation is critical in the western Delta yet the uncertainty in the time-averaged subsidence rates can be high, additional data about the distribution of subsidence rates is recommended in the western Delta for a higher level of certainty for the implementation of subsidence control measures. Also, analysis by Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) demonstrate that subsidence rates are decreasing with time. Therefore, the present-day subsidence rates are lower than those reported here and additional information is required to refine the delineation of priority areas based on present-day subsidence rates.

Uncertainty in the basal peat elevations and current elevations in the Delta also point to the need for additional data. Because the most recent topographic leveling in the Delta was completed in the 1970's, the peat thickness data presented here are about 20 years

old. These peat thickness data could be in error by as much as 6.5 feet because of subsidence that has occurred over the past 20 years. The peat thickness values are also uncertain for several islands as discussed above where data is sparse or lacking.

The effects of future subsidence on Delta levee stability have not been studied. Seepage and deformation are key processes that may be affected as the result of future subsidence. The area adjacent to the levee where levee stability is affected by subsidence and the time frame associated with this zone of influence needs to be determined through general and site specific analysis. Analysis should be conducted to determine the effects of future subsidence on levee deformation for different environments where the thickness of the peat and subsidence rates vary. Similarly, seepage analysis should be used to estimate volumes of seepage and the effects on levees for different subsurface materials, varying subsidence rates and different drain configurations.

Specific recommendations for future data collection efforts are as follows.
- Refine the delineation of priority areas by reducing the errors in subsidence rate estimates and peat thickness and determining present-day subsidence rates.
- Collect data for present-day subsidence rates and predict future subsidence rates. Present-day subsidence rates can be determined by measuring land-surface elevations in areas where there is historical data such as Mildred, Lower Jones and Bacon and determining land-surface elevations throughout the Delta at regular intervals. In the short-term, determination of soil organic carbon throughout the Delta in combination with measurement of land-surface elevations on selected islands will improve the delineation of priority areas.
- Future subsidence rates can be predicted by collecting data that will give more precision to the calculation of microbial oxidation described in this report. The evaluation and estimation of consolidation also require more data and analysis.
- Collect data for peat thickness. This can be done using geophysical methods or by determining land surface elevations and calculating the peat thickness using well-log data.
- Determine the effects of future subsidence on levee deformation and seepage.
- Continue to support development and pilot- and large-scale implementation of land- and water-management practices for subsidence mitigation.
- Integrate subsidence mitigation efforts with ecosystem restoration efforts.

APPENDIX A. DESCRIPTION OF COMPUTER MODEL FOR ESTIMATING THE RELATIVE MAGNITUDE OF THE CAUSES OF SUBSIDENCE AND MODEL RESULTS

A.1 Microbial Oxidation

The carbon flux data for Jersey Island collected from 1990 to 1992 (Deverel and Rojstaczer, 1996) was used to approximate the relation of microbial oxidation of organic carbon to soil organic carbon content. This relation was used to simulate subsidence due to microbial oxidation for Jersey Island at the study location of Deverel and Rojstaczer (1996). The mass of carbon lost by microbial oxidation was assumed to follow Michaelis-Menton kinetics (Conn and Stumpf, 1976):

$$CFLUX = (CFLUXMAX \times foc)/(Km - foc) \qquad (A.1)$$

where
$CFLUX$ = CO_2 loss from the soil in grams carbon cm^{-2} yr^{-1} due to microbial oxidation of organic carbon in the peat soil.
$CFLUXMAX$ = maximum CO_2 loss from the soil in grams carbon cm^{-2} yr^{-1}
Km = Michealis-Menton constant, and
foc = the fraction of organic carbon in the soil in grams carbon per g soil

The values of CFLUXMAX and Km were determined from annual averages of monthly carbon flux measurements for two sites on Jersey Island where soil organic matter content values of 0.28 and 0.22 were measured (Deverel and Rojstaczer, 1996). The foc values were estimated to be one-half of the soil organic matter content for the sites on Jersey and other sites in the Delta as per Broadbent (1960). The average annual soil temperature and depth of the groundwater at these two sites were nearly identical during the period of measurement (1990 - 1992). These two data points were used to develop a linear plot of the reciprocal of CFLUX versus the reciprocal of the foc. The slope of this plot is equal to Km/CFLUXMAX and the intercept is equal to 1/CFLUXMAX. For each year of model simulation, CFLUX was recalculated based on the change in foc as the result of the change in soil carbon during the previous time step. The change in land surface elevation due to oxidation was estimated by dividing the annual carbon flux by the soil bulk density and the foc.

The parameters for equation A.1 developed from the Jersey Island data were used to simulate microbial oxidation on Sherman Island. For the central Delta Islands, Mildred and Bacon islands and Lower Jones Tract, the elevation data for Mildred Island in Rojstaczer and others (1991) was used to determine the parameters for equation 2.1. The parameters were determined by model calibration against elevation measurements determined from 1924 through 1981 (Weir, 1950; Rojstaczer and others, 1991). The values for CFLUXMAX and Km determined for the Mildred Island calibration were then used to simulate land surface elevation changes for Lower Jones Tract and Bacon Island. Additional information about subsidence due to consolidation, wind erosion, burning, and withdrawal of natural gas and groundwater was also incorporated into the model.

A.2 Consolidation and Shrinkage

The amount of initial shrinkage and consolidation during reclamation was estimated from an empirical equation presented in Eggelsmann and others (1990) in which the consolidation is expressed as a function of the initial drainage depth in meters:

$$Consolidation = a \times (0.08 \times T - 0.066) \qquad (A.2)$$

where a is and empirical constant that is dependent
on the degree of decomposition and texture of the peat,
and T is the depth of initial drainage (assumed to be 6 feet).

Equation A.2 was used to estimate the total amount of consolidation due to initial drainage and was applied only once during simulation of subsidence for Jersey and Mildred islands. The empirical constant was assumed to have a value of 1.9 based on information presented in Eggelsmann and others (1990). For comparison, the amount of consolidation during initial drainage was also calculated using the drainage curves reported by Hanson and Carlton (1980). The results using the drainage curves were about 13 percent greater than those in which the Eggelsmann and others' (1990) equation was used.

A.3 Wind Erosion

Wind erosion of peat soils caused dust storms that affected Stockton, Lodi and Tracy prior to the early 1960's (Alan Carlton, former University of California Extenstion Specialist, personal communication, 1997). The prevailing westerly winds of oceanic air masses moving to the Central Valley caused dust storms primarily during May and June when wind speeds exceeded 15 miles per hour at a height of about 6 feet (Schultz and Carlton, 1959; Schultz and others, 1963). Carlton and Schultz (1956 – 1966) conducted experiments to determine the frequency and duration of dust storms caused by wind erosion of peat soils and methods for reducing wind erosion. Asparagus fields were a primary source of wind-eroded soil as the soil surface was mostly bare during May and June.

The Department of Water Resources (1980) reported values ranging from 0.1 inch per year based on personal communication from Alan Carlton to 0.25 to 0.5 inch per year from Weir (1950). Weir (1950) made no measurements of wind erosion and stated that "it may be as much as 0.25 to 0.5 inch per year." Carlton (1965) estimated wind erosion on Terminous Tract to be 0.57 inch per year from 1927 to 1957. This estimate was based on the elevation difference between a plot of land owned by Southern Pacific Railroad which was not farmed or cultivated but was surrounded by cultivated cropland. It is unclear whether the Southern Pacific Railroad land had been burned.

Crop histories in Thompson (1957) and the Weir transect notes (see Rojstaczer and others, 1991) were examined to determine the spatial distribution of crops grown on the islands where land surface elevation changes were simulated. Wind erosion was

calculated at varying rates of 0.1 to 0.57 inch per year where asparagus was grown or where the land was fallow. There was generally a shift from the planting of asparagus and other vegetable crops to corn in the Delta in the 1950's and 1960's and the model calculated minimal wind erosion after 1965.

A.4 Burning

Weir (1950) and Cosby (1941) estimated that the peat soils were burned once every 5 to 10 years. Burning probably occurred more frequently during World War II when potatoes were grown extensively (Rojstaczer and others, 1991). Burning was used to control weeds and diseases and to create ash for potatoes. Weir (1950) stated that 3 to 5 inches of peat was lost during burning. Burning was simulated differently for the islands depending on the distribution of crops.

It was assumed that most of the Delta organic soils were planted to potatoes from 1938 to 1945. Elevation loss on all five islands due to burning was simulated to be 4 inches per burning during 2.5 burnings during this time period. Individual cropping patterns were used to simulate burning during other time periods for Mildred and Bacon islands. Potatoes were grown on Mildred Island from 1930-1938 and 6 inches of soil loss during 1.5 burning was simulated during this time period. Potatoes were also a predominant crop on Bacon from 1930 to 1938 and 1945 to 1955 and 6 inches of soil loss during 1.5 burning was simulated during each of these time periods. Alan Carlton (former University of California Extension Specialist, personal communication, 1997) stated that there was no burning in the Delta after 1955.

A.5 Withdrawal of Natural Gas and Groundwater

To determine the subsidence due to natural gas withdrawal, sediment cores collected from channel islands were dated by determining the levels of cesium-137 at 1-inch depth intervals (Rojstaczer and others, 1991). The surface elevation of channel islands has remained at sea level since the 1850's even though sea level rose about 0.08 inches per year indicating that sediment has been deposited on these islands. The peak fallout of ceisum-137 occurred in 1963 and was identified 3 to 7 inches below the sediment surface in cores collected on channel islands adjacent to Twitchell, Bradford and Bethel islands and Webb Tract, indicating that the channel islands subsided since 1963.

From 1963 to 1988 when the cores were collected, sea level rose about 2 inches. Therefore, the amount of subsidence due to gas withdrawal was between 0.04 and 0.2 inches per year ((3 – 2 inches) divided by (1988-1963)) = 0.04 inch/year, ((7- 2 inches) divided by (1988-1963) = 0.2 inches/year)). For modeling of subsidence, 0.08 inch per year of subsidence as the result of gas withdrawal was estimated for Jersey Island based on the results of ceisum-137 results reported in Rojstaczer and others (1991) for the channel island adjacent to Bradford Island. Subsidence due to gas withdrawal was not simulated for the Sherman, Mildred and Bacon islands or Lower Jones Tract because elevation changes along the Weir transect were compared to a benchmark and structures that was also affected by these withdrawals. Records from the California Department of

Conservation, Division of Oil and Gas, indicate that gas production began to increase substantially in the mid-1950's and gas withdrawal was simulated as a contributor to subsidence in the model after 1955.

A.6 Simulation of Total Subsidence

The total annual depth of subsidence was estimated by summing the depths of subsidence due to the different causes. The model accreted the land surface as it progressed backward in time based on the mathematical representation of the processes described above. The foc and bulk density were estimated for the most recent elevation data and time step and were recalculated for each subsequent time step. For Sherman and Jersey Islands, the initial foc and bulk density were from Deverel and Rojstaczer (1996). For Mildred and Bacon islands and Lower Jones Tract the foc was estimated from the soil survey for San Joaquin County (Soil Conversation Service, 1992) to be 0.25. The bulk density for the surface (0 to 2 feet) soils for Mildred, Bacon and Lower Jones was estimated at 0.74 g/cm^3 from the relation for data for organic matter content and bulk density collected on Rindge and Empire tracts and Bouldin Island reported in Hanson and Carlton (1980). A regression equation ($r^2 = 0.50$) was fit to the all the data of the form.

$$log\ bulk\ density = 0.058 - 0.76\ x\ foc. \tag{A.3}$$

This equation was also used to estimate the bulk density at the beginning of each time step.

Subsidence and the microbial oxidation of organic carbon were simulated as a two-layer process based on data collected by Carlton (1966). The depth of soil affected by subsidence was assumed to be 5 feet. Carlton (1966) measured the depth of subsidence occurring in different layers on Venice Island from 1962 to 1966. Eighty-one percent of the total subsidence occurred in the upper 2 feet of the soil profile. Therefore, eighty-one percent of the organic carbon oxidation was simulated to occur in the upper 2 feet of the soil profile. The remainder was simulated to occur in the lower 3 feet. The foc was recalculated for each layer at each time step based on the change in the total mass of carbon for each layer. The final foc for the most recent and initial time step for the model for the lower layer was estimated at 0.375 based on information in Deverel (1983). The new oxidation rate was calculated for subsequent time steps using equation 2.1. The foc was not allowed to exceed 0.40 for either layer.

A.7 Model Results

Figure A.1 shows that there is good agreement between measured and modeled values for land-surface elevation changes for Bacon, Mildred and Lower Jones.
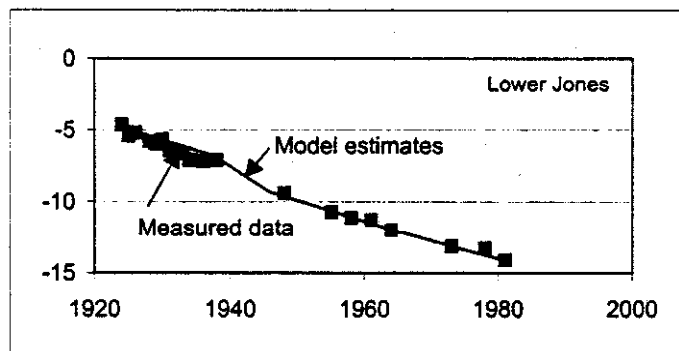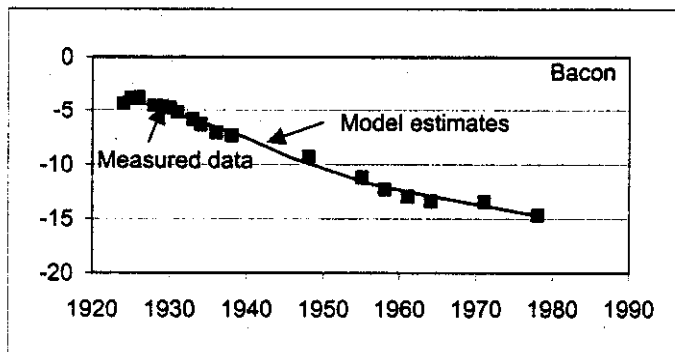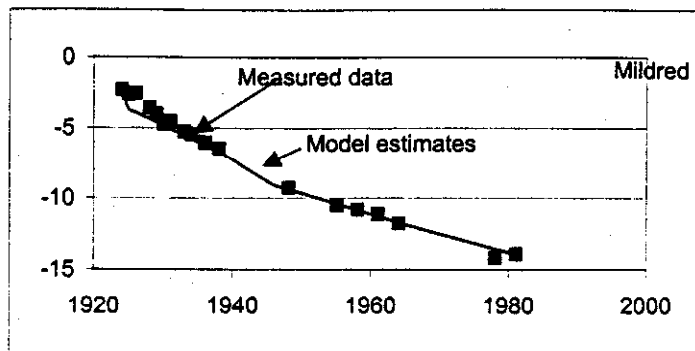
Figure A.1 Measured and model estimates for elevation changes for Mildred, Bacon and Lower Jones from 1924 to 1981. Squares represent measured data and solid lines represent model estimates. Elevation changes on the vertical axis are in feet above sea level.

APPENDIX B. METHODOLOGY, RESULTS, AND UNCERTAINTY ANALYSIS FOR THE DELINEATION OF PRIORITY AREAS FOR SUBSIDENCE MITIGATION.

A Geographic Information System developed by and housed at the Department of Water Resources Central District was used to delineate priority areas for subsidence mitigation based on time-averaged subsidence rates and peat thickness. The following describes the methodology, data, results and error analysis.

B.1 Determination of Areal Variability of Time-averaged Subsidence Rates

Two sets of US Geological Survey topographic maps were used to estimate the time-averaged rates of subsidence throughout the Delta from the early 1900's to 1976 through 1978. Specifically, topographic maps for the 1906-1911 mapping of the Delta at 1:31,680 scale were used to estimate land surface elevation on a 500-meter grid. The 1976 to 1978, 1:24,000 scale topographic maps were used to estimate land surface elevation for the same 500-meter grid. The difference in elevation between the two time periods was estimated to be the total depth of subsidence. The time-averaged rate of subsidence was calculated as the total amount of subsidence divided by the time interval that ranged from 60 to 72 years.

The error in the subsidence rate estimate results from the error in the elevation estimate from the topographic maps and the change in mean sea level datum from the early 1900's to 1976 to 1978. Early leveling in California used the average of tide level gauges in California for the mean sea level datum (Birdseye, 1925). The sea level datum for the 1976 to 1978 maps is the National Geodetic Vertical Datum of 1929 (NGVD-29) that was an average of mean sea level data for 21 tide stations in the United States (Ziloski and others, 1992). The error resulting from the comparison of the two datums for mean sea level was estimated by comparing the elevations for 10 benchmarks on both sets of maps. The elevations for the benchmarks for the maps published in the early 1900's were obtained from Birdseye (1925). The elevations for the same benchmarks using NGVD-29 were obtained from Joe Vukovitch, USGS, Denver.

The benchmark elevations for the maps published in the early 1900's were generally larger than the elevations using NGVD-29. The difference between the benchmark elevations for the maps published in the early 1900's and the elevations using NGVD-29 ranged from 0.008 to 0.704 feet. The average absolute difference was 0.275 feet. This difference was not accounted for in the determination of the time-averaged subsidence rates.

The error due to estimating the elevations from the contours is about one-half of the contour interval (5 feet) for the topographic maps or 2.5 feet (Joe Vukovitch, USGS, Denver, personal communication, 1996). The percent error for each subsidence rate was calculated as follows. The subsidence rate was calculated at each grid point as the difference between the elevations on the two maps plus or minus the error, divided by the time interval between the two mappings:

$$\text{subsidence rate} = (\text{Elev}1978 - \text{Elev}1906 +/- e)/T \qquad (B.1)$$

where Elev1978 is the elevation from the 1976 to 1978 USGS topographic maps,
Elev1906 is the elevation from the 1906 to 1911 USGS topographic maps,
e is the error associated with the elevation contours (1/2 the contour interval) and,
T is the time interval between the two elevation measurements.

The error was calculated as

$$e = E1978 + E1906 = +/- 5 \text{ feet} \qquad (B.2)$$

where E1978 and E1906 are the errors associated with the two sets of topographic maps (E1978 = E1906 = +/- 2.5 feet).

The percent error was calculated as the absolute value of 5 feet divided by the total subsidence multiplied times 100. The percentage error in the subsidence rate is dependent on the amount of subsidence that occurred during the approximately 70 years that elapsed between the surveying for the topographic maps.

B.2 Determination of the Areal Distribution of Peat Thickness

The peat thickness was calculated on the 500-meter grid as the difference between the basal elevation of peat or peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps. Peat or peaty mud of tidal wetlands includes the organic deposits derived from decayed vegetation that formed as the result of sea level rise during the last 7,000 years. Atwater's (1982) delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soil surveys. The areal distribution of the basal elevations of the peat deposits was delineated from about 1,200 borehole logs collected through 1980.

The majority of the locations of the borehole logs were on or near the levees. The peat thickness data was compared with the delineation of organic soils or highly organic mineral soils in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993). Where there were discrepancies between the two sources of information for the extent of peat soils, the soil survey data was assumed to be correct.

B.3 Areal Variability of Soil Characteristics

The delineation of soil series as mapped in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993) were entered into the GIS developed by the Department of Water Resources Central District in digital form. The soil organic matter content was the primary soil characteristic of interest. The soil organic matter content was estimated for the 11 soil series which were either organic soils or highly organic mineral soils based on the data provided in the soil surveys. Specifically, the soil surveys for San Joaquin and Sacramento counties provided a range of values for percent soil organic matter. The midpoint of this range was assigned to that series in the GIS database. The percent organic matter for the soil series mapped in Contra Costa County was estimated from the data provided in the soil surveys for San Joaquin and Sacramento Counties.

B.4 Geographic and Hydrographic Data

Geographic and hydrographic data was obtained as USGS Digitial Line Graphs at 1:100,000 scale from the Teale Data Center.

B.5 Delineation of Priority Areas for Subsidence

The areal distribution of time-averaged subsidence rates and peat thickness was used to delineate priority areas for subsidence mitigation. The first priority area includes those lands where the time-averaged subsidence rates were greater than 1.5 inch per year and the peat thickness was greater than 10 feet. The second priority area includes lands where the time-averaged subsidence rates were greater than 1.5 inch per year and the peat thickness was less than or equal to 10 feet.

B.6 Results of Delineation of Priority Areas

Table B.1. Acreages by island for the 2 priorities for subsidence mitigation. Priority 1 includes areas where the time-averaged subsidence rate was greater than 1.5 inch per year and the peat thickness was greater than 10 feet. Priority 2 includes areas where the subsidence rate was greater than 1.5 inch per year and the peat thickness was less than or equal to 10 feet.

Priority 1   **Priority 2**

Quimby	35	Quimby	35
Grand	250	Staten	144
King	70	King	1,478
Bethel	70	Brannan	1,440
Woodward	130	Bethel	350
Holland Tract	410	Tyler	610
Medford	570	Sherman	390
Rindge	600	Bradford	860
Sherman	1,480	Holland Tract	930
Empire	600	Lower Jones	2,340
McDonald	910	Bouldin	2,940
Bacon	790	Orwood	840
Jersey	670	Victoria	1,000
Bradford	710	Venice	1,270
Twitchell	1,720	Palm	1,020
Tyler	2,180	Empire	2,570
Brannan	1,700	Mandeville	2,350
Staten	1,400	Rindge	3,680
Venice	950	Webb Tract	2,400
Bouldin	1,860	Bacon	3,830
Mandeville	1,940	McDonald	4,940
Webb Tract	3,920	Woodward	310
Total	22,900	Total	35,700

B.7 Uncertainty in the Spatial Analysis

Uncertainty in the spatial analysis is the result of uncertainty in the thickness of the peat soil and the error in the estimation of the subsidence rate. The subsidence rate error is the result of errors associated with the use of topographic elevations as described above and the use of different datums for the 2 surveys for the topographic maps published in 1906 to 1911 and 1976 to 1978. In general, large errors in the subsidence rate correspond to areas of the lowest time-averaged subsidence rates. The error in the subsidence rate estimate due to the mapping error is 50 percent or less for much of the Delta. The error in the estimation of the subsidence rate generally increases approaching the periphery of the Delta. The error in the western, eastern, southern and northern edges of the Delta generally approaches or exceeds 100 percent.

Specifically, the error in the subsidence rate on the central Delta islands, Bouldin, Island, Venice Island, Empire Tract, Mandeville Island, Bacon Island, Lower Jones Tract, McDonald Island and Empire Tract is generally less than 50 percent. Also, the error in the subsidence rates for the west-central and east-central islands, Webb Tract, Twitchell Island, Bradford Island, Rindge Tract and King Island is also generally lower than 50 percent.

Figure B.1 shows the exponential decrease in the percent error in the subsidence rate as the result of mapping errors with increasing time-averaged subsidence rates. The error was calculated for the average time between elevation measurements of 69 years for the topographic maps used in determining the total elevation change. The key questions related to the error for the purpose of determining the priority areas based on time-averaged subsidence rates are: 1) Is the distribution of subsidence rates consistent with the what is known about the distribution of present-day subsidence rates? and 2) What is the error associated with assignment of areas to one of the two categories (less than and greater than 1.5 inch per year) for subsidence rates?

The first question can be answered qualitatively based on recently collected data for subsidence for selected areas of the Delta. Specifically, data from Rojstaczer and Deverel (1995), Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) are consistent with the spatial distribution of subsidence rates presented here. Subsidence rates in the central Delta (Lower Jones Track, Bacon and Mildred islands) are greater than in the western Delta (Sherman and Jersey islands). However, subsidence has not been measured extensively throughout the Delta so that it is impossible to compare rates for all the islands. The subsidence rates in Figure 2 are generally consistent with what is known about subsidence and organic soils in the Delta (Prokopovitch, 1985). The highest soil organic matter contents and subsidence rates are in the central Delta. The soils are lower in organic matter content and subsidence rates are lower approaching the margins of the Delta

The second question can be answered based on the distribution of error for subsidence rates. Further error analysis using the data shown Figure B.1 and the distribution of error

in the subsidence rate was used to determine the effect of the distribution of error on the assignment of priorities.

Figure B.1. Relation of error in the estimation of the time-averaged subsidence rate to the subsidence rate.
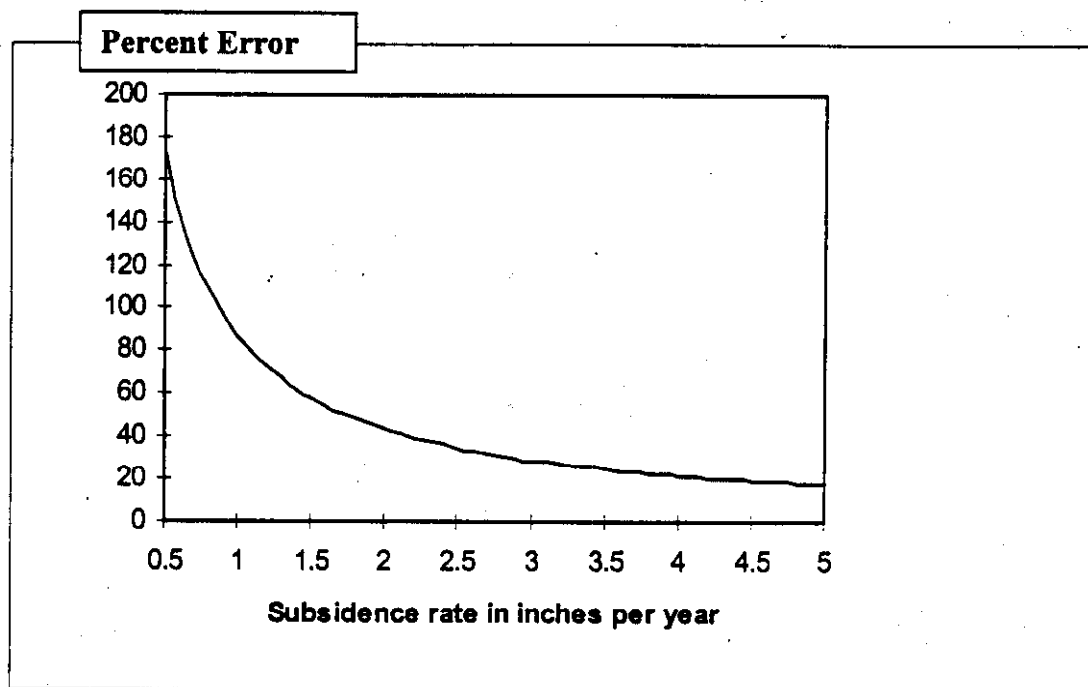
Using the data shown in Figure B.1 and the distribution of error in the subsidence rate, the lowest time-averaged rate of subsidence that could be erroneously classed as a rate of over 1.5 inch per year is 0.7 inch per year (the error associated with the rate of 0.7 inch per year is 122 percent). The highest time-averaged subsidence rate that could be classed under 1.5 inch per year is 2.3 inches per year (the error associated with the rate of 2.3 inches per year is 36 percent). Data for Sherman Island and Webb Tract was used to evaluate the effect of errors on the acreage within each priority area.

The data for these two islands represent the variability in the data set and the error analysis illustrates the possible range in calculated acreage in the two priority areas. About 80 percent of Sherman Island in the western Delta have peat greater than 10 feet thick but most of the time-averaged subsidence rates were below 1.5 inch per year. In contrast, Webb Tract has experienced time-averaged subsidence rates generally greater than 2.5 inches per year and about 50 percent of the island have peat soils greater than 10 feet thick. Webb Tract has the largest acreage in priority 1. The acreage in priority 1 on Sherman Island is about equal to the median. Sherman has one of the smallest acreage in priority 2.

The results of the error analysis are shown in Table B.2. The range of acreage on Webb Tract for priority 1 shows that the acreage in priority 1 could be overestimated by 54 % and underestimated by less than 1 %. For priority 2, the range in acreage on Webb Tract

shows that the acreage in priority 2 could be overestimated by 24 % and underestimated by 10%. In contrast, the ranges of acreage in each priority for Sherman Island are large, ranging up to 1,000 percent. The subsidence rates for Sherman are lower than Webb and the error associated with the subsidence-rate estimate is higher and the range of acreage classified in each priority is large. The results of this analysis point to the need for additional data collection for subsidence rates in the western Delta and other areas where time-averaged subsidence rates are mapped as1.5 inch per year or less.

Table B.2. Range in acreage for each priority for Sherman Island and Webb Tract.

Island	Estimated acreage in priority 1	Range	Estimated acreage in priority 2	Range
Sherman	1,480	0 - 5,410	390	41 – 2,200
Webb	3,920	1,770 - 3,940	2,400	1,860 – 2,650

The areal distribution of the estimation error for the peat thickness was not determined. The density of borehole data and the error in the land-surface elevation primarily determines the error. The land-surface elevation error is due to leveling error in the determination of land-surface elevation that is about plus or minus 2.5 feet and the subsidence that has occurred since 1974 (about 1 to 4 feet). The total land-surface elevation error ranges from about –1.5 to 6.5 feet.

Table B.3 shows the number and average density of data points from borehole logs used to estimate the peat thickness. The data in Table B.3 does not present the entire story relative to'the density of data points for peat thickness. Some data points were used for islands besides those for which they are assigned in Table B.3 since the data for peat thickness was extrapolated across channels. Also, most of the data points are on the levees so that the range of area without borehole data for each island varies substantially. In general, data densities greater than 200 acres per point result in moderate to high uncertainty in the estimation of the basal peat elevation for large areas of the islands.

Of those islands where the density of peat thickness data is greater than 200 acres per point, only 6 have acreage in the 2 priorities (Orwood Tract, Victoria Island, Brannan-Andrus Island, King Tract, Tyler Island and Grand Island). Brannan-Andrus Island, King Tract and Tyler Island have significant acreage in the 2 priority areas. Grand Island is mapped as having a large area of deep peat but has little acreage in the two priority areas because of the low time-averaged subsidence rates. Although there is uncertainty in the delineation of the priority areas for subsidence mitigation, the delineation is based on the available data and provides a starting point for further data collection efforts to better define areas for subsidence mitigation.

Table B.3. Number of data points, acreage and data density for each island used to delineate the distribution of peat thickness.

Island	Number of points	Acreage	Data density (acres/point)
Medford	31	1,219	39
Jersey	60	3,471	58
Bradford	28	2,051	73
Palm	32	2,436	76
Mandeville	68	5,300	78
Woodward	23	1,822	79
Bethel	43	3,500	81
Bacon	66	5,625	85
Sherman	105	9,937	95
Webb Tract	58	5,490	95
Twitchell	36	3,516	98
Venice	31	3,220	104
Empire	28	3,430	123
Canal Ranch	23	2,996	130
Holand	31	4,060	131
Coney	7	935	134
Bouldin	44	6,006	137
Staten	61	9,173	150
McDonald	39	6,145	158
Lower Jones	33	5,894	179
Hotchkiss	17	3,100	182
Byron	36	6,933	193
Rindge Tract	35	6,834	195
Terminous	50	10,470	209
Lower Roberts	48	10,600	221
Upper Jones	27	6,259	232
Orwood	13	4,138	318
Brack	14	4,873	348
Victoria	19	7,250	382
Brannan-Andrus	31	13,000	419
Bishop	3	2,169	723
King	4	3,260	815
New Hope	8	9,300	1,163
Tyler	7	8,583	1,226
Grand	3	17,010	5,670
Veale	0	1,298	
Shin Kee	0	1,016	
Rio Blanco	0	705	
Union	0	22,202	
Shima	0	2,394	
Ryer	0	11,880	

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